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Inspection Procedures for Military Wood Structures

Ghassan Al-Chaar, Mohsen A. Issa,
and John R. Hayes Jr.

March 2002

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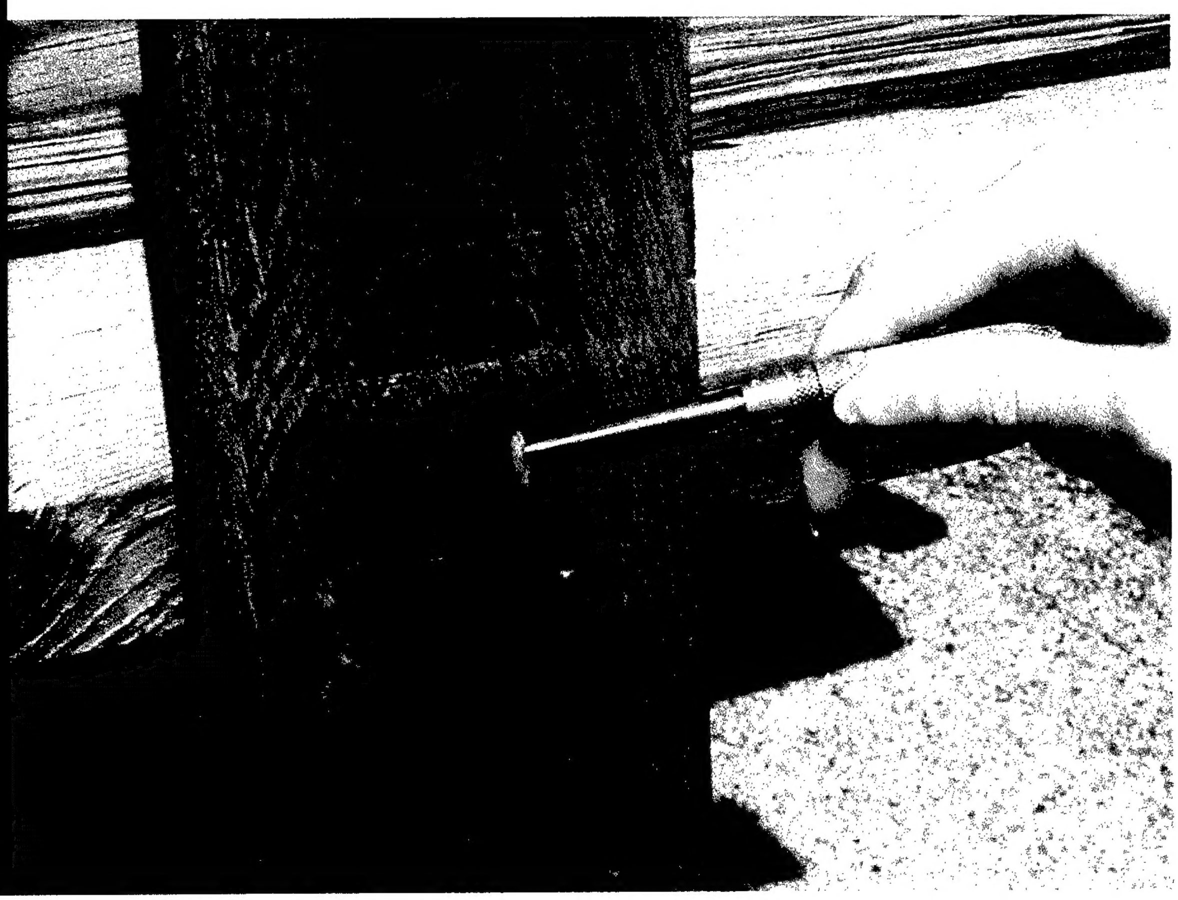

Construction Engineering
Research Laboratory

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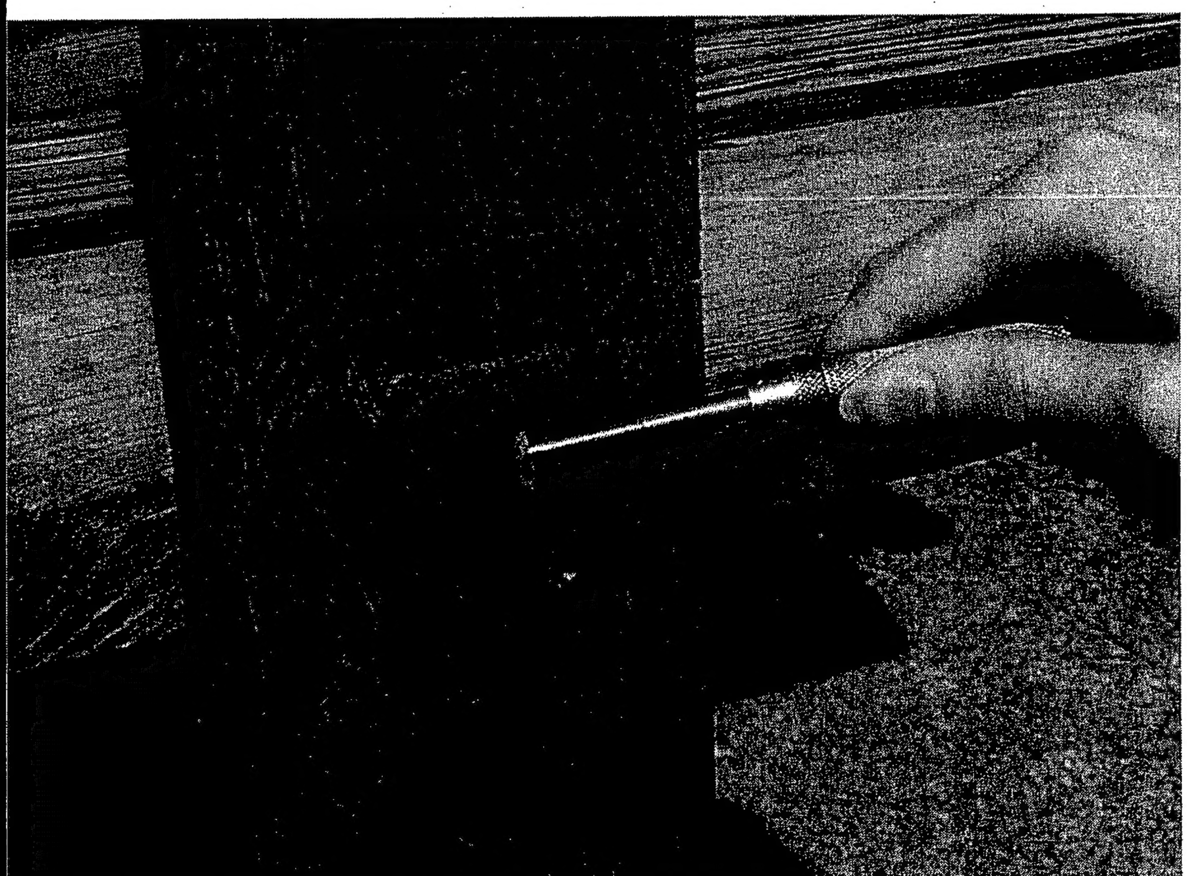


Foreword

This study was conducted for Headquarters, U.S. Army Corps of Engineers (HQUSACE) under Military Interdepartmental Purchase Request (MIPR) E87950422, "Technical Support – Structural Program," dated 30 September 1995. The technical reviewer was David C. Bohl, CECW-EW.

The work was performed by the Materials and Structures (CF-M) Branch of the Facilities Division (CF), Construction Engineering Research Laboratory (CERL). The CERL Principal Investigator was Dr. John R. Hayes, Jr. Part of this work was done under contract by Dr. Mohsen Issa, University of Illinois – Chicago. The technical editor was Gordon L. Cohen, Information Technology Laboratory – Champaign. Martin J. Savoie is Chief, CEERD-CF-M, and L. Michael Golish is Chief, CEERD-CF. The Technical Director of the Facility Acquisition and Revitalization business area was Dr. Paul A. Howdyshell, CEERD-CV-ZT, and the Director of CERL is Dr. Alan W. Moore.

CERL is an element of the Engineer Research and Development Center (ERDC), U.S. Army Corps of Engineers. The Commander and Executive Director of ERDC is COL John W. Morris III, EN, and the Director is Dr. James R. Houston.

Contents

Foreword 2

List of Figures and Tables 6

1 Introduction 9

1.1 Background 9
1.2 Objective 11
1.3 Approach 11
1.4 Scope 11
1.5 Mode of Technology Transfer 12
1.6 Units of Weight and Measure 12

2 Wood Identification 13

2.1 Commercial Species and Geographical Locations in the United States 13
2.2 Commercial Wood Product Sources and Applications 14
2.3 Overview of Wood Morphology 14
2.3.1 Heartwood and Sapwood *15*
2.3.2 Growth Rings *15*
2.4 Wood Characteristics 16
2.4.1 Grain *17*
2.4.2 Figure *18*
2.4.3 Texture *18*
2.4.4 Color *18*
2.4.5 Weight *18*
2.5 General Wood Identification Procedures 19
2.6 Visual Identification Key for Softwoods Commonly Used in Construction 20
2.7 Characteristics and Applications of Major Commercial Softwoods 24
2.7.1 Southern Cypress *24*
2.7.2 Douglas Fir (DF) *25*
2.7.3 Western Hemlock (WCH) *26*
2.7.4 Red Pine *27*
2.7.5 Southern Longleaf Pine (LL) *28*
2.7.6 Western White Pine (IWP) *29*
2.7.7 Redwood *30*
2.7.8 Engelmann Spruce (ES) *31*
2.8 Other Commercially Used Softwoods 32
2.8.1 True Fir (Eastern Species) *32*
2.8.2 Western True Fir (WF) *32*
2.8.3 Eastern Hemlock (HEM) *32*
2.8.4 Western Larch (L) *32*

2.8.5 *Sugar Pine (SP)* ... 33

3 Grading Concepts and Procedures ... 34

3.1 Stress-Graded Lumber ... 35

3.2 Nonstress-Graded Lumber ... 35

3.3 Appearance Lumber ... 35

3.4 Visual Grading ... 37

3.4.1 *Density* ... 37

3.4.2 *Decay* ... 38

3.4.3 *Heartwood and Sapwood* ... 38

3.4.4 *Slope of Grain* ... 38

3.4.5 *Knots and Checks* ... 39

3.4.6 *Shake* ... 40

3.5 Mechanical Grading ... 40

3.5.1 *Procedures for Deriving Mechanical Properties* ... 40

3.5.2 *Basic Mechanical Grading Protocol* ... 41

4 Structural Properties of Wood ... 42

4.1 Softwood Lumber Manufacture ... 42

4.1.1 *Size* ... 42

4.1.2 *Surfacing* ... 42

4.2 Principal Mechanical Properties ... 43

5 Wood Durability Risk Factors In Service ... 52

5.1 Overview of Wood Deterioration Factors ... 52

5.2 Effects of Aging ... 53

5.3 Physical Causes of Wood Deterioration ... 53

5.3.1 *Mechanical Damage* ... 53

5.3.2 *Heat Damage* ... 54

5.3.3 *Ultraviolet Exposure* ... 54

5.3.4 *Chemical Exposure* ... 54

5.3.5 *Incidental Effects of Corrosion* ... 55

5.4 Biogenic Causes of Wood Deterioration ... 57

5.4.1 *Enabling Factors* ... 57

5.4.2 *Varieties of Wood-Damaging Organisms* ... 58

5.4.3 *Deterioration Impacts and Protective Actions* ... 62

6 Comparing Current Condition With As-Built Condition ... 65

6.1 Inspection ... 65

6.1.1 *Introduction* ... 65

6.1.2 *Preventive Maintenance* ... 69

6.1.3 *Evaluation of Revised Loadings* ... 69

6.1.4 *Evaluation of Distressed Structure* ... 70

6.2 Methods of Detecting Deterioration ... 70

6.2.1 *Methods for Detecting Exterior Deterioration* ... 70

6.2.2 *Methods for Detecting Interior Deterioration* ... 74

6.3 Inspection Procedures ... 78

6.3.1 *Pre-Inspection Procedures* ... 79

6.3.2 Individual Component Inspection *80*
6.3.3 Records and Reports *82*
6.4 Rating 82
6.5 Code Changes Spanning 1944 – 1991 84
6.5.1 General Design Requirements *84*
6.5.2 Modifications to Design Values *86*
6.6 Inspection of Specific Structural Types 94
6.6.1 Heavy Timber Buildings *94*
6.6.2 Heavy Trusses *95*
6.6.3 Light Trusses *96*
6.6.4 Bridges *97*
6.6.5 Pole Structures *98*

7 Serviceability and Strength-Reduction Characteristics of Wood 100
7.1 Factors Influencing Serviceability of Wood Structures 100
7.1.1 Loads *100*
7.1.2 Duration of Load *103*
7.1.3 Temperature *103*
7.1.4 Moisture *107*
7.1.5 Chemicals *110*
7.1.6 Weathering *112*
7.1.7 Checks, Shakes, and Splits *114*
7.2 Predictive Service Life Testing of Components 116
7.2.1 Service Life Tests *117*
7.2.2 ASTM Systematic Approach *119*

8 Summary 121

References 122

Glossary 127

Appendix A: Engineering Information for Wood Structure Inspectors 140

Appendix B: Sample Forms Used for Detailed Wood Inspections 145

CERL Distribution 151

Report Documentation Page 152

List of Figures and Tables

Figures

1 Schematic drawing of a tree cross-section. 15
2 Schematic diagram illustrating the three principal planes in wood. 16
3 Possible sawing patterns for lumber....................17
4 Flowchart for wood identification using low magnification or visual inspection....................20
5 Southern Cypress, flat-cut cross-section. 24
6 Douglas Fir, rotary-cut cross-section....................25
7 Western Hemlock, quarter-sawn cross-section....................26
8 Red Pine, quarter-sawn cross section. 27
9 Southern Longleaf Pine, flat-cut cross-section....................28
10 Western White Pine, flat-cut cross-section. 29
11 Redwood, flat-cut cross-section. 30
12 Engelmann Spruce, flat-cut cross-section....................31
13 Specimen shapes and loads for determining the mechanical properties of wood: (a) axial tension, (b) transverse tension, (c) shear, (d) axial compression, (e) transverse compression, (f) side hardness, and (g) static bending. 46
14 Static bending test. 46
15 Axial tension test. 47
16 Axial shear test. 47
17 Axial compression test with deformation gauge. 48
18 Typical failure for axial compression test. 48
19 Transverse compression test. 49
20 Ultraviolet light degradation....................56
21 Wood infected with brown rot fungi. 61
22 Basic decay detection process....................63
23 Column damaged by passing objects. 66
24 Typical type of existing repair. 66
25 Another typical type of existing repair....................67
26 End split in diagonal member. 67
27 Major damage due to decay. 68
28 Fracture in diagonal member....................68

29 Tension failure in diagonal member. 69
30 Material testing procedures for decay. 71
31 Examples of decay fungus fruiting bodies 72
32 Overview of inspection process. 73
33 Pick test for detecting early wood decay. 74
34 Using a moisture meter. 76
35 Extracting cores with an incrememt borer to detect rot. 77
36 One example of a sonic inspection device for detecting internal defects in wood 78
37 Using a V meter for nondestructive ultrasonic inspection of internal wood condition 79
38 Levels of decay potential for wood exposed to the weather in aboveground service based on a climate index derived from standard temperature and rainfall data. 80
39 Deep seasoning check in Douglas Fir section. 81
40 Sample condition rating form for wood trusses. 83
41 Relationships for moisture content, temperature, relative humidity, and shrinkage. 108
42 Weathering process of round and square timbers. 114
43 Discontinuities in wood: shake (a) and check (b). 115
44 Effect of separation on cross-sectional properties of beam: (a) solid section, (b) split at neutral plane, (c) check at neutral plane 116
45 Degradation factors affecting the service life of building components and materials. 118
46 Outline of systematic approach for developing predictive service life tests. 120

Tables

1 Color and figure of common kinds of domestic softwoods. 19
2 Organizations promulgating softwood grades. 36
3 Commercial species of softwood lumber. 37
4 Representative value ranges for n and Q/P ratios. 39
5 American standard lumber sizes for stress-graded and nonstress-graded lumber. 43
6 Density and shrinkage* (air-dry density, 12 – 15 percent moisture content and total shrinkage from green to zero-moisture content). 44
7 Mechanical properties at dry conditions. 44
8 Mechanical properties at green conditions[1]. 45
9 Effect of moisture content on strength properties[1]. 45
10 Relative effects of various energy forms on wood. 56
11 Checklist of inspection equipment. 73

12 Lumber designation changes. 85

13 Code changes with respect to normal conditions of use........ 86

14 Adjustment factors in NDS codes spanning 1944 – 1991........ 87

15 Various design values. 89

16 Duration-of-load adjustment factors used in structural design.* 103

17 Approximate middle trend effects of temperature on mechanical properties of clear wood at various moisture conditions.* 105

18 Some typical ASTM property measurement tests for wood. 117

19 Some degradation factors affecting wood and ASTM aging tests for those factors. 118

1 Introduction

1.1 Background

The approach of United States involvement in World War II triggered a massive military construction program of unprecedented scope. Many buildings erected during the period were simple housing and administrative facilities, but huge numbers of them were aircraft hangars — a relatively new type of technical construction that was needed to outfit and maintain the rapidly expanding Army and Navy aircraft fleets. During this era, wood was considered the principal raw material for building construction, even for mammoth structures such as the Navy's dirigible hangars. Among the largest timber structures ever built, these blimp hangars measured approximately 1000 x 265 ft, reaching a center height of 120 ft; the roof supports were framed arches joined with ring connectors and bolts. At other times during U.S. history, a building of such size would at a minimum incorporate steel structural frames, but during the war era metals were reserved mostly for use in military ordnance, machinery, vehicles, aircraft, and ships.

During the wartime military construction boom, the level of demand for new wood buildings was almost inconceivable. This demand overwhelmed not only the supply of usable timber, but also the pool of designers, tradespeople, and supervisors experienced in wood construction techniques. Furthermore, in order to meet facility demand and construction schedules, a number of adaptations had to be made to traditional practice. For example:

- although 15 pounds per square inch (psi) was traditionally considered a typical roof load for standard timber construction, design loads of 20 psi, 30 psi, or more were frequently required (and applied) in the field
- lumber of 1200 psi allowable flexural stress (1200f) was reassigned an allowable flexural stress of 1800 psi to serve in more demanding applications
- because the supply of 1200f lumber was insufficient, large quantities of non-stress-graded lumber were used without appropriate design modifications
- demand for seasoned lumber exceeded supply, so significant quantities of unseasoned lumber were procured and used in construction.

In short, the necessities of war often drove builders during World War II to use unconventional construction approaches, and these created many problems that would not be acceptable in a traditional wood construction project. These problems fall into several broad categories:

- *Inappropriate design techniques*. Examples include inadequate joint design, insufficient camber due to use of unseasoned lumber, improperly operating doors that were not designed to correctly account for truss deflection, unsuitable design of compression members, trusses designed with inappropriately small height-to-span ratios, and application of metal design methods to timber construction.
- *Use of inappropriate lumber*. As noted above, ungraded, nonstructural, and/or unseasoned lumber was often used out of necessity created by short supplies of good-quality structural timber.
- *Fabrication and erection errors*. Examples include inappropriate handling and storage of lumber before fabrication, members fabricated 'off-spec' and forced into place, substandard workmanship, misapplication of fasteners and related construction details, elimination of necessary truss bracing, and resawing lumber without regarding it.
- *Inadequate maintenance*. Examples include the failure to tighten bolts as lumber seasoned in place, improper reinforcement or repair techniques, and failure to correct ponding problems that resulted from poor drainage.

After World War II ended, there were compelling operational and economic reasons to continue using huge numbers of the war-era wooden structures. Thousands of them are still in productive use by the Army and other military services today even though they were originally classified in real property management terms as *temporary* construction (i.e., an intended service life of 5 years). Despite problems such as those noted above, most of the surviving wooden buildings have proven to be serviceable (if not perfect) well beyond their design life. Because only a few cases of structural collapse were reported during the war, it is reasonable to assume that many of the original structural deficiencies were identified during inspection and subsequently eliminated through renovation, reinforcement, or other corrective measures.

The structural elements in older wooden buildings usually have an unknown loading history, and it must be assumed that they have deteriorated over time. In general, careful periodic inspection of wood buildings will reveal structural distresses in time to take corrective measures and prevent a major structural failure. It is the building inspector's responsibility to check structural members to determine whether they meet modern life-safety standards.

Army Regulation (AR) 420-70 requires inspection of trusses, roof framing, and other structural items every 2 to 5 years (AR 420-7, par 3.21, app C), but no Army criteria documents provide specific procedures to guide building inspectors through a detailed evaluation of wood structures. In order to promote an effective inspection program for timber structures, the Construction Engineering Research Laboratory, Engineer Research and Development Center, was tasked to prepare a document to provide the inspection engineer with basic information on wood identification, characteristics and properties affecting structural strength, durability factors, and deterioration processes.

1.2 Objective

The principal objective of this document is to present a comprehensive set of guidelines for structural inspection of military wood buildings.

1.3 Approach

An extensive literature review was conducted and structural engineering expertise was applied to prepare the guidelines. This document addresses the following wood structure inspection issues:

- wood types, grades and mechanical properties
- consolidated procedures in checklist and flow chart format
- qualitative visual inspection procedures that minimize the wide variations in judgment that often occur
- procedures for nondestructive qualitative field and laboratory tests to determine the basic mechanical properties.

1.4 Scope

The information presented here is intended to support Army personnel in the field tasked with inspection of wood structures. It is not intended to serve as guidance or a substitute for structural engineering expertise. If the findings of a condition inspection raise questions or concerns about structural integrity, then it is essential to immediately seek the assistance of a trained and qualified structural engineer.

1.5 Mode of Technology Transfer

This document is published to support implementation of AR 420-70, par 3.21, app C. It is recommended that the contents of this report be considered for adaptation or inclusion in an Army Corps of Engineers Technical Instruction.

1.6 Units of Weight and Measure

U.S. standard units of measure are used throughout this report. A table of conversion factors for Standard International (SI) units is provided below.

SI conversion factors		
1 in.	=	2.54 cm
1 ft	=	0.305 m
1 yd	=	0.9144 m
1 sq in.	=	6.452 cm^2
1 sq ft	=	0.093 m^2
1 sq yd	=	0.836 m^2
1 cu in.	=	16.39 cm^3
1 cu ft	=	0.028 m^3
1 cu yd	=	0.764 m^3
1 gal	=	3.78 L
1 lb	=	0.453 kg
1 psi	=	6.89 kPa
°F	=	(°C x 1.8) + 32

2 Wood Identification

2.1 Commercial Species and Geographical Locations in the United States

Trees are divided into two broad classes, usually referred to as "hardwoods" and "softwoods." However, these terms have little to do with the actual hardness of the species that fall into each respective category: a number of softwood species are harder than various hardwoods. Major sources of softwood species are spread across the United States, except for the Great Plains, where only small areas are forested.

Hardwoods fall into the taxonomic subdivision called Angiosperms, also called broadleafs. They are considered porous woods due to the presence of vessels or pores. With some exceptions, most hardwoods grow east of the Great Plains. The following classification is based on the principal producing region for each wood:

- **Southern hardwoods:** Ash, Basswood, American Beech, Butternut, Cottonwood, Elm, Hackberry, Pecan Hickory, True Hickory, Honeylocust, Black Locust, Magnolia, Soft Maple, Red Oak, White Oak, Sassafras, Sweetgum, American Sycamore, Tupelo, Black Walnut, Black Willow, and Yellow-Poplar.
- **Northern and Appalachian hardwoods:** Ash, Aspen, Basswood, Buckeye, Butternut, American Beech, Birch, Black Cherry, American Chestnut, Cottonwood, Elm, Hackberry, True Hickory, Honeylocust, Black Locust, Hard Maple, Soft Maple, Red Oak, White Oak, American Sycamore, Black Walnut, and Yellow Poplar.
- **Western hardwoods:** Red Alder, Oregon Ash, Aspen, Black Cottonwood, Golden Chinquapin, Oregon White Oak, Pacific Madrone, Bigleaf Maple, Paper Birch, Tanoak, and California Black Oak.

Softwoods fall within the subdivision called Gymnosperms, also called conifers. They are considered nonporous because they lack the vessels or pores found in hardwoods. Softwoods comprise needle-bearing trees such as pines, spruces, firs, hemlocks, and cedars, and are associated with three general producing regions:

- **Western:** Alaska Cedar, Incense Cedar, Port Orford Cedar, Douglas Fir, White Firs, Western Hemlock, Western Larch, Lodgepole Pine, Ponderosa

Pine, Sugar Pine, Western White Pine, Western Red Cedar, Redwood, Engelmann Spruce, and Sitka Spruce.
- **Northern:** Northern White Cedar, Balsam Fir, Eastern Hemlock, Jack Pine, Red Pine, Eastern White Pine, Eastern Red Cedar, Eastern Spruces, and Tamarack.
- **Southern:** Atlantic White Cedar, Baldcypress, Southern Pine, and Eastern Red Cedar.

2.2 Commercial Wood Product Sources and Applications

Hardwoods are used in construction for flooring, architectural woodwork, trim, and paneling. These items are usually available from lumberyards and building supply dealers. Most hardwood lumber and dimension stock are remanufactured into furniture, flooring, pallets, containers, dunnage, and blocking. Hardwood lumber and dimension stock are available directly from the manufacturer, through wholesalers and brokers, and in some retail yards.

Softwoods are available directly from the sawmill, wholesale and retail yards, or lumber brokers. Softwood lumber and plywood are used in construction for forms, scaffolding, framing, sheathing, flooring, ceiling trim, paneling, and cabinets. It is also used for structural applications such as truss members, studs, and other load bearing elements. Softwoods may also appear in the form of shingles, sash, doors, other millwork, and some rough products such as round treated posts.

Because softwoods are more suitable for building construction, and thus more commonly used, this report will focus on presenting a detailed description of the different types of softwoods used in everyday construction.

2.3 Overview of Wood Morphology

Figure 1 presents a schematic diagram of a typical tree cross-section showing the various parts of the wood. The outer portion of the section depicts the bark, which consists of two layers — outer and inner bark. The outer layer is composed of dead tissue that functions as a protective covering for the tree, while the inner bark consists of living tissue that transports nourishment throughout the tree. The layer that separates the bark from the inner portion of the tree (sapwood and heartwood) is called the cambium, the purpose of which is to produce new growth in the tree. The sapwood and heartwood, as shown in Figure 1, are the portions of the tree that

are used for lumber manufacture (especially the heartwood). The pith is the center of the tree stem or trunk.

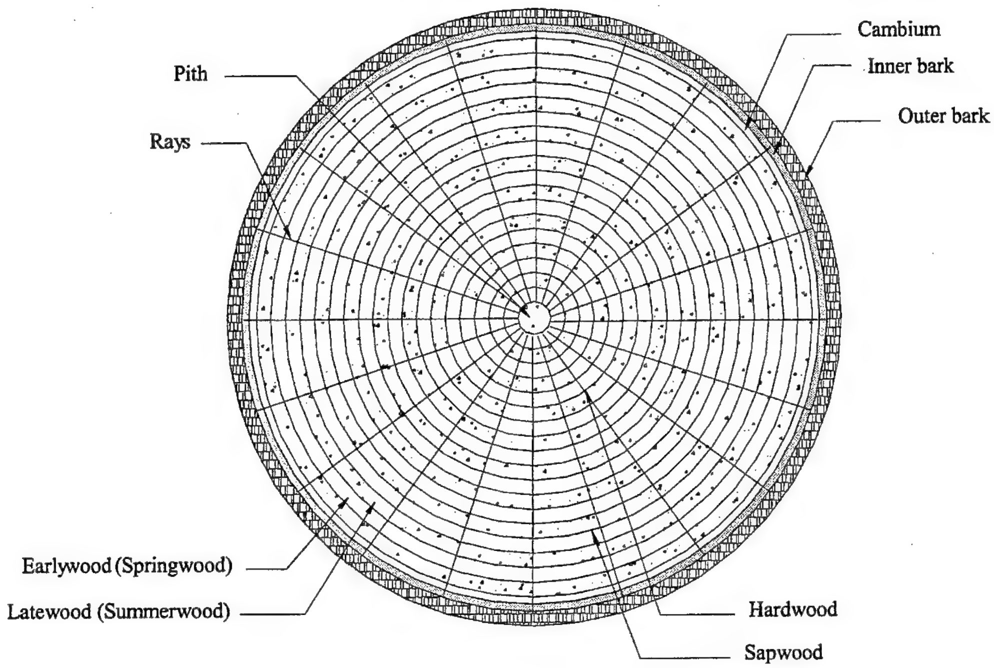


Figure 1. Schematic drawing of a tree cross-section.

2.3.1 Heartwood and Sapwood

The stem portion inside the bark and cambium is what we know as wood. In most woods, this tissue appears in two zones of contrasting colors — heartwood and sapwood. The outer zone just inside the cambium is always white, cream-colored, or yellowish, and is the sapwood. Sapwood commonly ranges from 1.5–2 in. in thickness. Heartwood, the inner wood zone, is the generally darker tissue that is more durable and resistant to decay when exposed to weather. The amount of heartwood relative to sapwood in a stem varies from species to species. Even within species, the relative amount of heartwood differs.

2.3.2 Growth Rings

In temperate zones, growth rings appear as a band of light tissue adjacent to a band of darker tissue. They indicate the tree's yearly growth in diameter. They are created by the difference in density and color between wood formed early and wood formed late in the growing season (i.e., earlywood and latewood).

Construction lumber is visually graded for strength on the basis of the number of growth rings per in. across the end of a board. Dense grades are based on a rela-

tively large number of growth rings per square in. and indicate lumber of greater strength than that with fewer rings.

2.4 Wood Characteristics

Field identification can often be made on the basis of readily visible characteristics such as color, odor, density, presence of pitch, or grain pattern. Where more positive identification is required, a laboratory investigation of the microscopic anatomy of the wood can be made. Wood is identified as an orthotropic material, i.e., it has unique characteristics and independent mechanical properties in the directions of three mutually perpendicular axes, transverse, radial, and tangential. The three principal planes in wood are transverse (cross section), radial, and tangential as shown in Figure 2. The transverse axis is parallel to the grain; the radial axis is normal to the growth rings; and the tangential axis is perpendicular to the grain but tangential to the growth rings. Various sawing techniques are used in wood construction in order to more effectively exploit grain structure for the specific application. The three basic sawing patterns for lumber are illustrated in Figure 3.

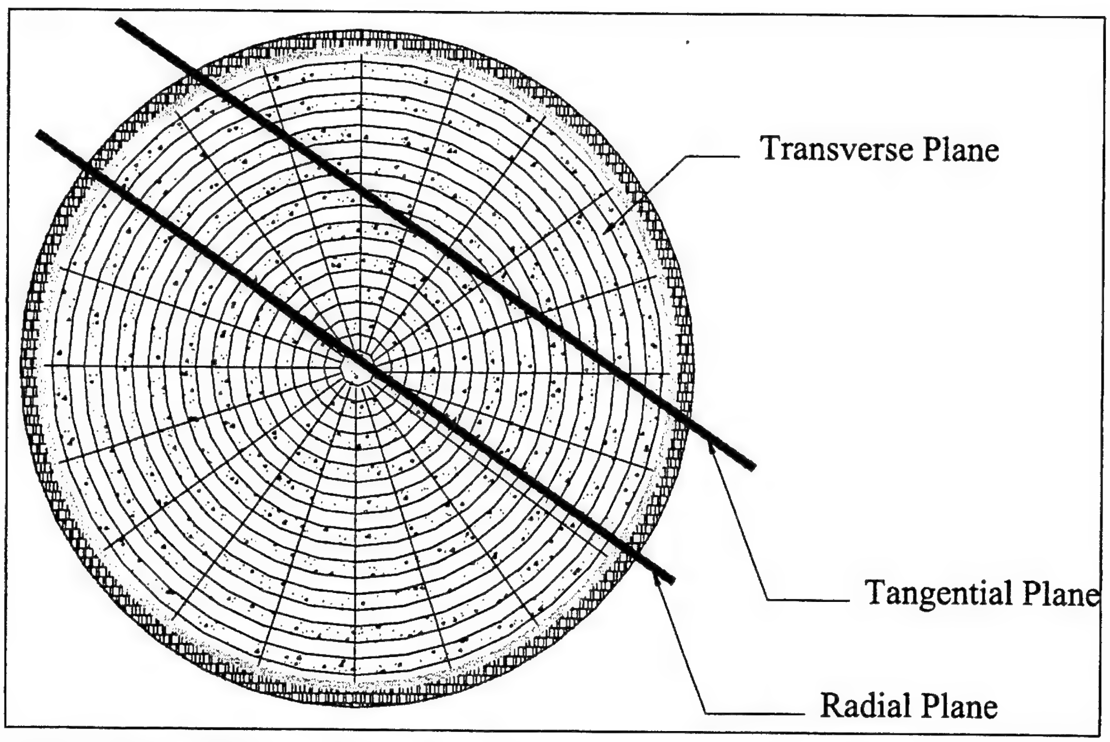


Figure 2. Schematic diagram illustrating the three principal planes in wood.

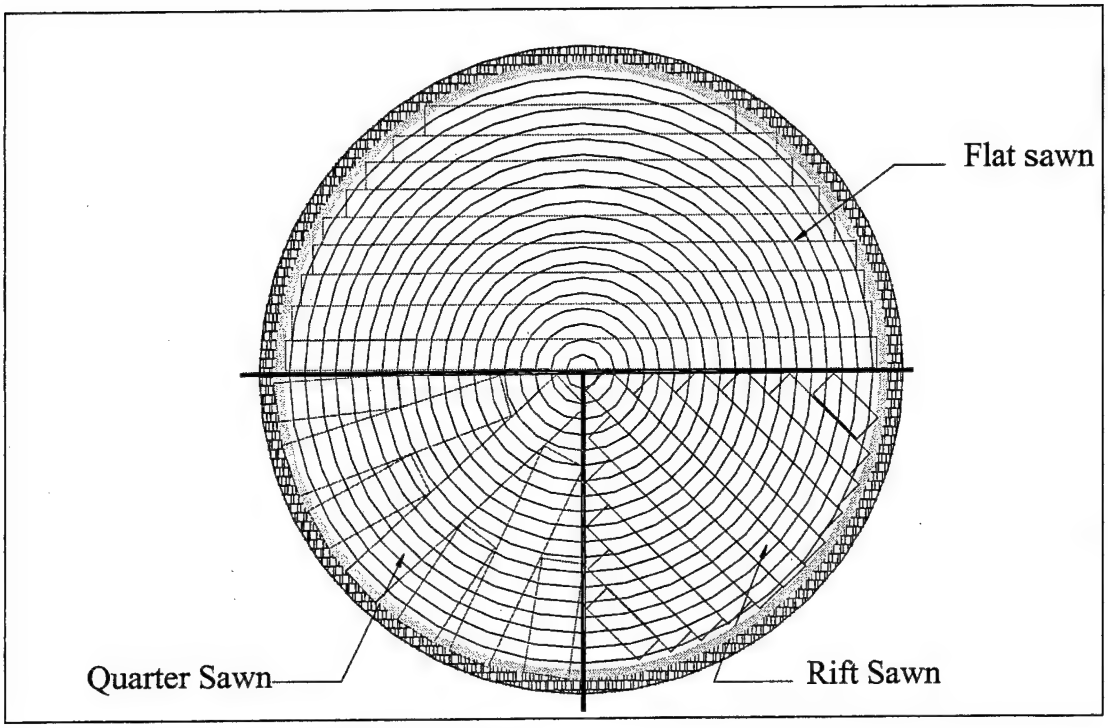


Figure 3. Possible sawing patterns for lumber.

Selection of the right timber for a particular job relies upon a selection of appropriate properties. Timber of different species may have different properties, so identification checks are very important. Appearance, finish, and texture of a wood surface are best discussed using terminology identified below.

2.4.1 Grain

Grain is the direction of fibers relative to the axis of the longitudinal surface of the wood under examination. Wood splits across its grain quite easily.

- ***Straight grain:*** indicates that the fibers run parallel to the vertical edges of the tree, which gives maximum strength.
- ***Diagonal grain:*** has fibers inclined to the edge of the wood. This may be a serious defect as it has a considerable weakening effect, and is brought about by sawing the wood diagonally in the timber yard.
- ***Spiral grain:*** where the fibers occur either in clockwise or counter-clockwise spirals (another source of structural weakness).
- ***Irregular or cross-grain:*** deflection of grain around knots, or the way grain slopes through a piece.
- ***Interlocked grain:*** where successive layers of fibers are inclined in different directions. Sometimes called alternating spiral grain, interlocked irregular grain produces what is known as roe figure. Timbers having an inter-

locked grain show a banded or striped figure on quarter-sawn stock, the striping varying according to the degree of interlock present.

- ***Wavy grain:*** creates the popular fiddle-back figure.

2.4.2 Figure

Figure is the pattern on the wood. It is produced by such things as the color difference between the earlywood and latewood, the pattern made by the growth rings as seen on the longitudinal surfaces, and the actual type of grain present. The amount of ray material present will also affect the figure. Table 1 presents the types of figures in both plainsawed and quartersawed lumber of the more common types of softwood species used in construction.

2.4.3 Texture

Texture refers to the prevailing size of the cell cavities; texture may range from very fine to very coarse according to the species of wood. It may be described as even (i.e., uniform) or uneven, the difference being that uneven texture is to be seen in woods in which there is a marked contrast between the earlywood and latewood (as in the ring-porous woods), while no such contrast exists in even-textured wood. Texture can be chosen to a certain extent, but sometimes it is necessary to use a coarse-textured wood, then polish or paint seal it to meet the objectives of the applications.

2.4.4 Color

Most species can be described as cream-colored or brownish, and brown hues may be eithera red-brown or a gold-brown. Sapwood is always very pale, while heartwood is generally darker. Some figure patterns show up not because of actual color variations but because leaning fibers (interlocked or wavy grain) cause a variation in reflectivity. When durability is an important requirement for a given purpose, then color is a useful indicator: in general pale timbers are perishable and darker timbers are durable. Table 1 describes in a general manner the color of heartwood of the more common types of softwood species used in construction.

2.4.5 Weight

The weight of any given species of timber will vary according to the conditions under which it was grown, the soil, its position in the tree, age and many other factors. All weights are given for timber in the dry state, i.e., when dried to the range 12–15%, as would be required for indoor use. Softwoods vary from about 4.5–9.0

lb/ft^3 (350–700 kg/m^3) but hardwoods are much more variable, 2.6–15.4 lb/ft^3 (200–1200 kg/m^3) being the general range. When selecting a species for a particular mechanical use, weight is obviously more important than appearance because strength is related to it. Weight is the best indication of likely strength. When it is necessary to use an alternative timber for a job, then species of similar weight should be looked at first.

Table 1. Color and figure of common kinds of domestic softwoods.

Species	Color of dry heartwood	Type of figure in-	
		Plain sawed lumber or rotary-cut veneer	Quarter sawed lumber or quarter-sliced veneer
Southern Cypress	Light yellowish brown to reddish brown	Conspicuous irregular growth ring	Distinct, not conspicuous growth-ring stripe
Douglas Fir	Orange red to red; sometimes yellow	Conspicuous growth ring	Distinct, not conspicuous growth-ring stripe
True firs (Eastern species)	Nearly white	Distinct, not conspicuous growth ring	Faint growth-ring stripe
True firs (Western species)	Nearly white to pale reddish brown	Conspicuous growth ring	Distinct, not conspicuous growth-ring stripe
Eastern Hemlock	Light reddish brown	Distinct, not conspicuous growth ring	Faint growth-ring stripe
Western Hemlock	Light reddish brown	Distinct, not conspicuous growth ring	Faint growth-ring stripe
Western Larch	Russet to reddish brown	Conspicuous growth ring	Distinct, not conspicuous growth-ring stripe
Red pine	Orange to reddish brown	Distinct, not conspicuous growth ring	Faint growth-ring stripe
Southern Longleaf pine	Orange to reddish brown	Conspicuous growth ring	Distinct, not conspicuous growth-ring stripe
Sugar pine	Light creamy brown	Faint growth ring	None
Western white pine	Cream to light reddish brown	Faint growth ring	None
Redwood	Cherry to deep reddish brown	Distinct, not conspicuous growth ring; occasionally way and burl	Faint growth-ring stripe; occasionally way and burl
Engelmann spruce	Nearly white	Faint growth ring	None

2.5 General Wood Identification Procedures

The flowchart presented as Figure 4 depicts a fast method for identifying the various softwood species used in building construction. This flowchart does not represent a detailed accounting of the types of softwoods used and the various aspects of

wood identification such as color, figure, and texture of the wood section under inspection.

A more detailed procedure is presented in Section 2.6 for identifying softwoods by species under a magnification of tenth order (hand lens) or visual inspection of the wood sample. All the softwood species described earlier are represented in Section 2.6 in more detail than Figure 4. This identification procedure presents an ideal description of the gross physical characteristics of the wood such as color, odor, weight, hardness, grain, etc. The procedure pertains to select softwood species widely used in building construction.

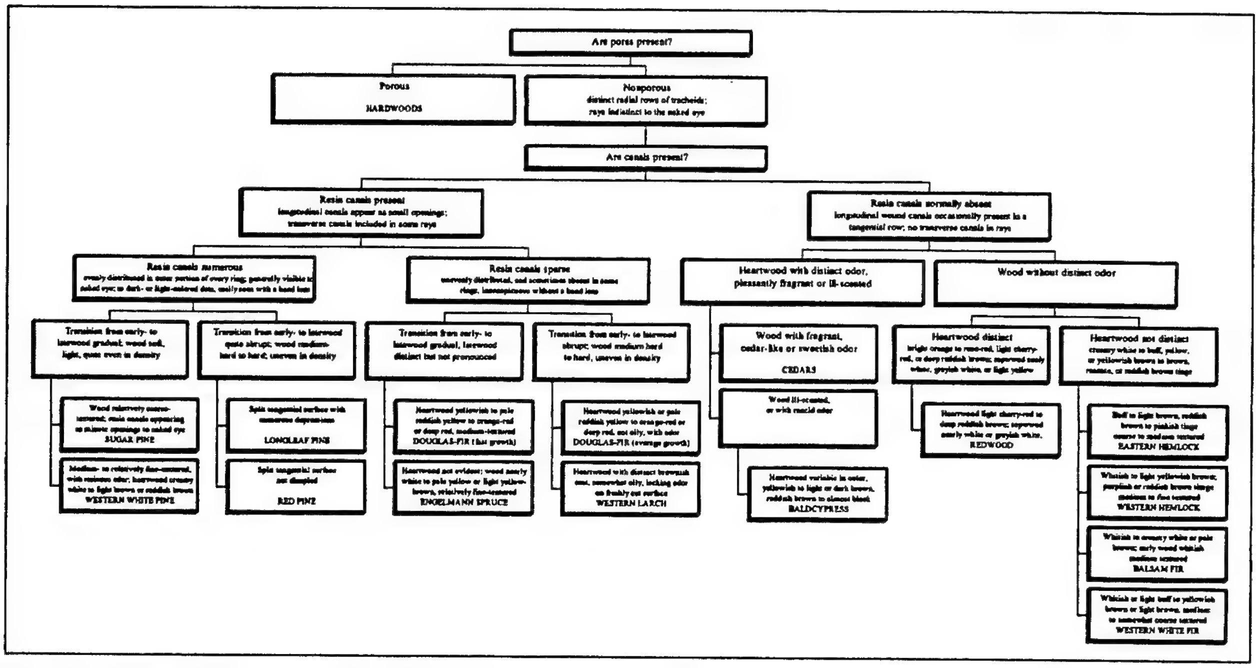


Figure 4. Flowchart for wood identification using low magnification or visual inspection.

2.6 Visual Identification Key for Softwoods Commonly Used in Construction

This identification key is designed to visually differentiate the more important temperate North American softwoods that are suitable for construction purposes, based on features visible with a 10X hand lens or without magnification. The key can be used in conjunction with Figure 4 in order to better visualize the identification process.

1. Woods with pores (with vessels).

HARDWOODS

1. Woods nonporous (without vessels); cross sections consist of distinct radial rows of tracheids; rays indistinct to the naked eye.

GO TO 2

2. Resin canals present; longitudinal canals appear as small openings mostly in the outer part of the latewood; transverse canals included in some rays, which then appear larger.

GO TO 3

2. Resin canals normally absent; longitudinal wound (traumatic) canals occasionally present in a tangential row; no transverse canals in rays.

GO TO 6

3. Resin canals numerous, evenly distributed in outer portion of every ring; generally visible to the naked eye as dark- or light-colored dots, easily seen with a hand lens.

GO TO 4

3. Resin canals sparse, unevenly distributed, and sometimes absent in some rings (occasionally appear as 2 to many in a tangential row), barely visible to the naked eye as light or dark dots; inconspicuous without a hand lens.

GO TO 5

4. Transition from earlywood to latewood gradual; wood soft, light, quite even in density.

A. Wood relatively coarse-textured; resin canals appear as minute openings to the naked eye.

SUGAR PINE

B. Wood medium- to relatively fine-textured, with resinous odor; heartwood creamy white to light brown or reddish brown, turning darker with age and exposure, split tangential surface not dimpled; resin canals appear as light- or dark-colored dots.

WESTERN WHITE PINE

4. Transition from earlywood to latewood quite abrupt; wood medium-hard to hard; uneven in density.

A. Split tangential surface with numerous depressions that give it a dimpled effect.

LONGLEAF PINE

B. Split tangential surface not dimpled.

RED PINE

5. Transition from earlywood to latewood gradual; latewood distinct but not pronounced.

A. Heartwood yellowish to pale reddish yellow to orange-red or deep red; wood with characteristic odor on freshly cut surface, medium-textured, contours of growth rings frequently wavy.

DOUGLAS FIR (fast growth)

B. Heartwood not evident; wood nearly white to pale yellow or light yellow-brown, lustrous, relatively fine-textured; split tangential surface only occasionally dimpled.

ENGELMANN SPRUCE

5. Transition from earlywood to latewood abrupt; wood medium hard to hard, uneven in density.

A. Heartwood yellowish or pale reddish yellow to orange-red or deep red; wood with characteristic odor on freshly cut surface; not oily; contours of growth rings often wavy; resin canals frequently in short tangential lines.

DOUGLAS FIR (average growth)

B. Heartwood with distinct brownish cast, wood lacking characteristic odor on freshly cut surface, somewhat oily; contours of growth rings usually smooth; resin canals sometimes in tangential groups of 2-5, or single and sporadic, not in tangential lines.

WESTERN LARCH

6. Heartwood with distinct odor, pleasantly fragrant or ill-scented.

GO TO 7

6. Wood without distinct odor.

GO TO 9

7. Wood with fragrant, "cedar-like" or sweetish odor.

CEDARS

7. Wood ill-scented, or with rancid odor.

GO TO 8

8. Heartwood variable in color, ranging from yellowish to light or dark brown, reddish-brown to almost black, with rancid odor on freshly cut surfaces; wood often greasy or oily; contours of the individual rings irregular.

BALDCYPRESS

9. Heartwood distinct, bright orange to rose-red, light cherry-red, or deep reddish brown; sapwood nearly white, grayish-white, or light yellow.

A. Heartwood light cherry-red to deep reddish brown; sapwood nearly white or grayish white, wood coarse-textured, light to moderately light, soft to moderately hard.

REDWOOD

9. Heartwood not distinct; wood creamy white to buff, yellow, or yellowish brown to brown, with or without a lavender, roseate, or reddish-brown tinge.

A. Wood buff to light brown, sometimes with a reddish-brown to pinkish tinge; earlywood usually with a reddish tinge; transition from earlywood to latewood semi-abrupt to abrupt; coarse and uneven grained, coarse to medium-textured.

EASTERN HEMLOCK

B. Wood whitish to light yellowish-brown; sometimes with a purplish or reddish-brown tinge; transition from earlywood to latewood semi-abrupt to abrupt; even grained, medium- to fine-textured.

WESTERN HEMLOCK

C. Wood whitish to creamy white or pale brown; early wood whitish, changing gradually to a darker lavender late wood (color contrast more pronounced in wide rings); transition from earlywood to latewood gradual to semi-abrupt; straight and even-grained, medium-textured.

BALSAM FIR

D. Wood whitish or light buff to yellowish-brown or light brown; earlywood whitish, changing gradually to a darker lavender latewood (color contrast more pronounced in wide rings); transition from earlywood to latewood gradual to

semi-abrupt; generally straight and quite even-grained, medium- to somewhat coarse-textured.

WESTERN WHITE FIR

2.7 Characteristics and Applications of Major Commercial Softwoods

The following section and Figures 5 through 12 summarize key characteristics present a comprehensive look at applications of various softwood species used in the North American construction industry.

2.7.1 Southern Cypress

Other names: Swamp Cypress, Louisiana Cypress, Gulf Cypress, Red Cypress, Yellow Cypress, White Cypress, Cypress.

Location: Grows in swampy lowlands of the southeastern United States; the northern extreme of its growth area is the coastal plains of Virginia.

Use: Principally for construction work where resistance to decay is required; excellent for weather boarding and roofing shingles.

Density: 460 kg/m^3 (29 lb/ft^3).

Durability: Heartwood is generally highly resistant to decay, particularly the darker-colored wood; it is classified as durable.

Figure 5. Southern Cypress, flat-cut cross-section.

2.7.2 Douglas Fir (DF)

Other names: Red Fir, Douglas Spruce, Yellow Fir, British Columbia Pine, Columbian Pine, Oregon Pine.

Location: Extends from the Rocky Mountains to the Pacific Coast and from Mexico to Central British Columbia and Alberta, Canada.

Use: Mostly for construction purposes in the form of lumber, timbers, piles, and plywood; its strength and large dimensions make it one of the best-known timbers for heavy structural purposes.

Density: 480 kg/m^3 (30 lb/ft^3).

Strength: Of at least average density, is strong for its weight; narrow-ringed, low-density material is unsuitable for structural purposes; unsuitable for conventional bent work.

Durability: Heartwood is moderately durable and resistant to preservative treatment; penetration is improved by incising.

Figure 6. Douglas Fir, rotary-cut cross-section.

2.7.3 Western Hemlock (WCH)

Other names: West Coast Hemlock, Hemlock Spruce, Western Hemlock Spruce, Western Hemlock Fir, Prince Albert Fir, Gray Fir, Silver Fir, Alaska Pine.

Location: Grows along the Pacific coast of Oregon and Washington and in the northern Rocky Mountains, north to Canada and Alaska.

Use: Principally for pulpwood, lumber, and plywood; the lumber goes largely into building material, such as sheathing, siding, subflooring, joists, studding, planking, and rafters; used where the lower strength is acceptable and a decay-resistant timber is not required.

Density: 450 kg/m^3 (28 lb/ft^3).

Strength: Not as strong as Douglas Fir but stronger than spruce.

Durability: Timber is similar to spruce in durability and is unsuitable for use in exposed situations, especially as it resists preservative treatment; has a high moisture content when green and seasons more slowly than Douglas Fir.

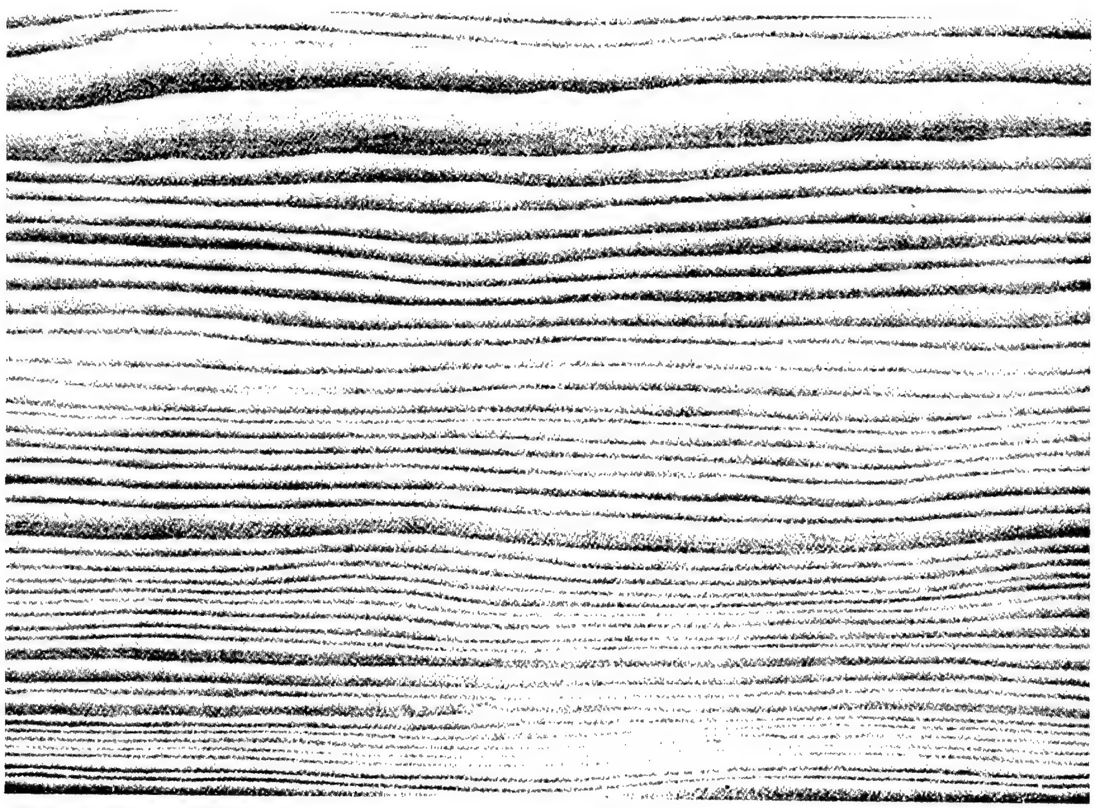


Figure 7. Western Hemlock, quarter-sawn cross-section.

2.7.4 Red Pine

Other names: Norway Pine, Hard Pine, Pitch Pine.

Location: Grows in the New England States, New York, Pennsylvania, and the Lake States.

Use: Principally for lumber and to a lesser extent for piles, poles, cabin logs, posts, pulpwood, and fuel; it goes mostly into building construction, siding, flooring, sash, doors, blinds, general millwork, and boxes, pallets, and crates.

Density: 460 kg/m^3 (29 lb/ft^3).

Strength: Average strength, i.e., stronger than white pine.

Durability: Not highly durable but superior to white pine and spruce; moderately resistant to preservative treatment.

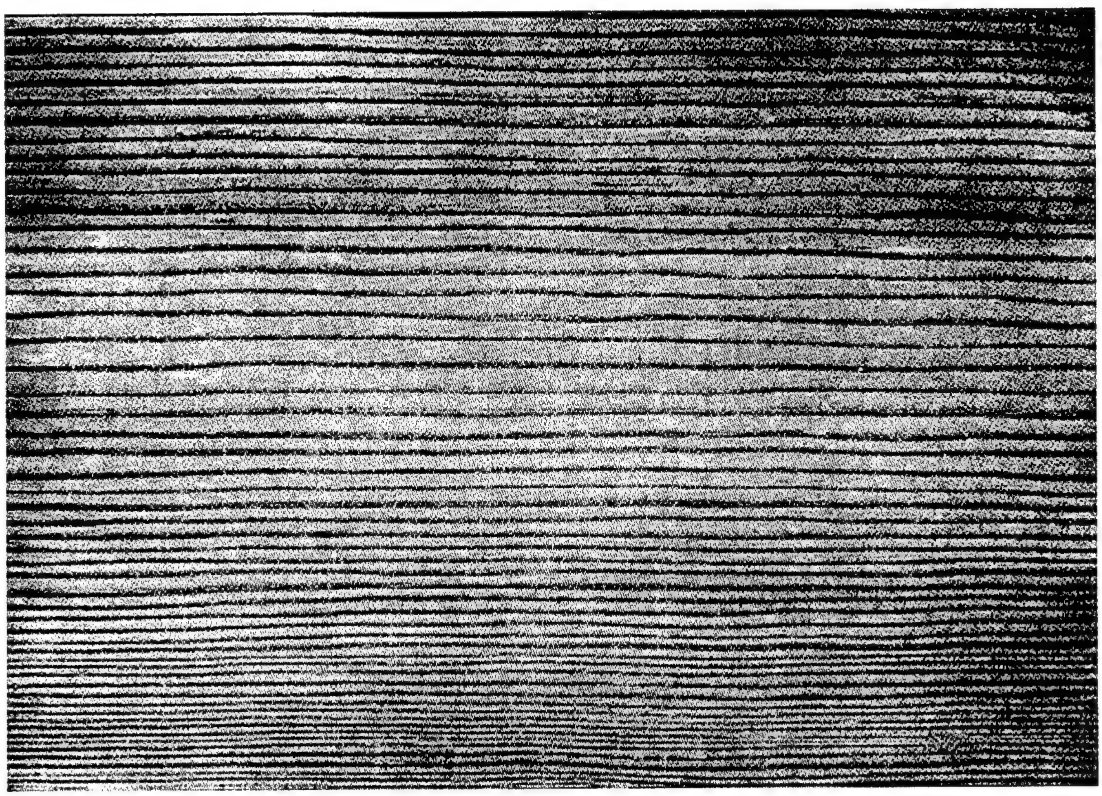


Figure 8. Red Pine, quarter-sawn cross section.

2.7.5 Southern Longleaf Pine (LL)

Other names: n/a

Location: Grows from eastern North Carolina southward into Florida and westward into eastern Texas.

Production: Southern and south Atlantic states; states that lead in production are Georgia, Alabama, North Carolina, Arkansas, and Louisiana.

Use: Dense southern pine is used extensively in construction of factories, warehouses, bridges, trestles, and docks in the form of stringers, beams, posts, joists, and piles.

Density: 590 kg/m^3 (37 lb/ft^3).

Strength: Stronger than most commercial softwoods.

Durability: Heartwood is lightly resistant to decay.

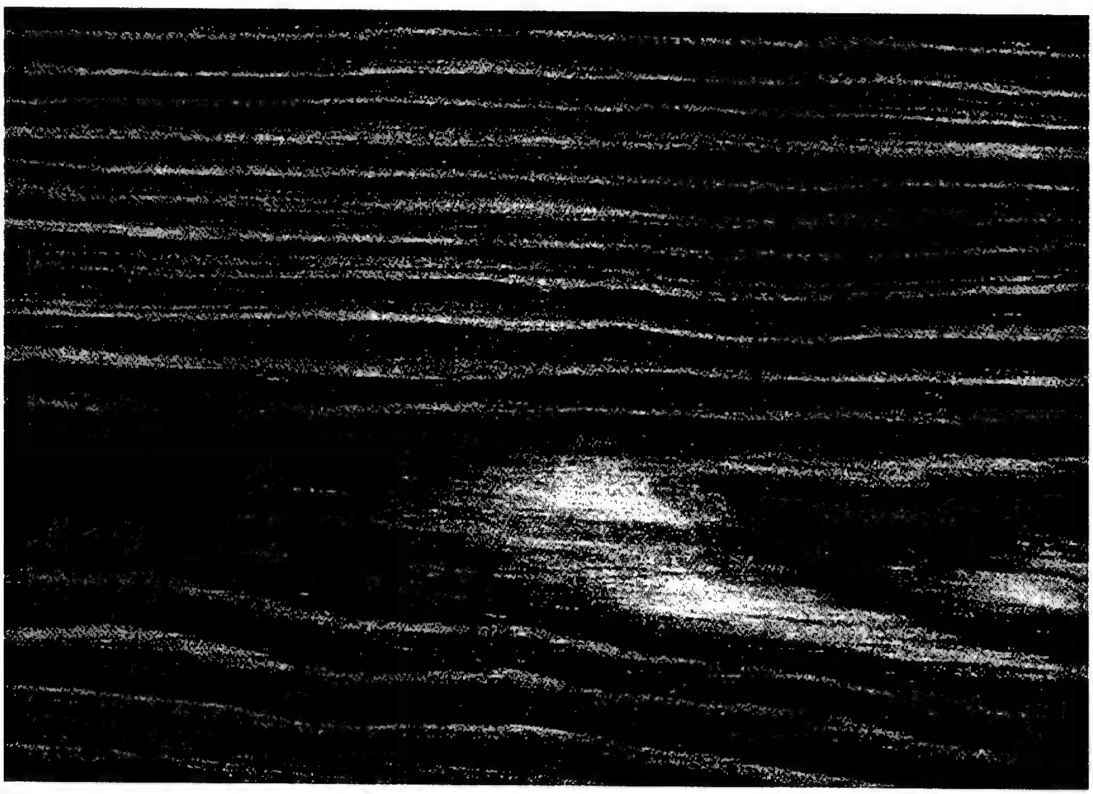


Figure 9. Southern Longleaf Pine, flat-cut cross-section.

2.7.6 Western White Pine (IWP)

Other names: Idaho White Pine, White Pine.

Location: Approximately four-fifths of the supply comes from Idaho with the remainder mostly from Washington; small amounts are cut in Montana and Oregon.

Use: Mainly for building construction, matches, boxes, patterns, and millwork products, such as sash, frames, doors, and blinds; in building construction, boards of the lower grades are used for sheathing, knotty paneling, subflooring, and roof strips.

Density: 380 kg/m^3 (24 lb/ft^3).

Strength: Low in strength compared with other commercial species of pine.

Durability: Not durable; moderately resistant to preservative treatment.

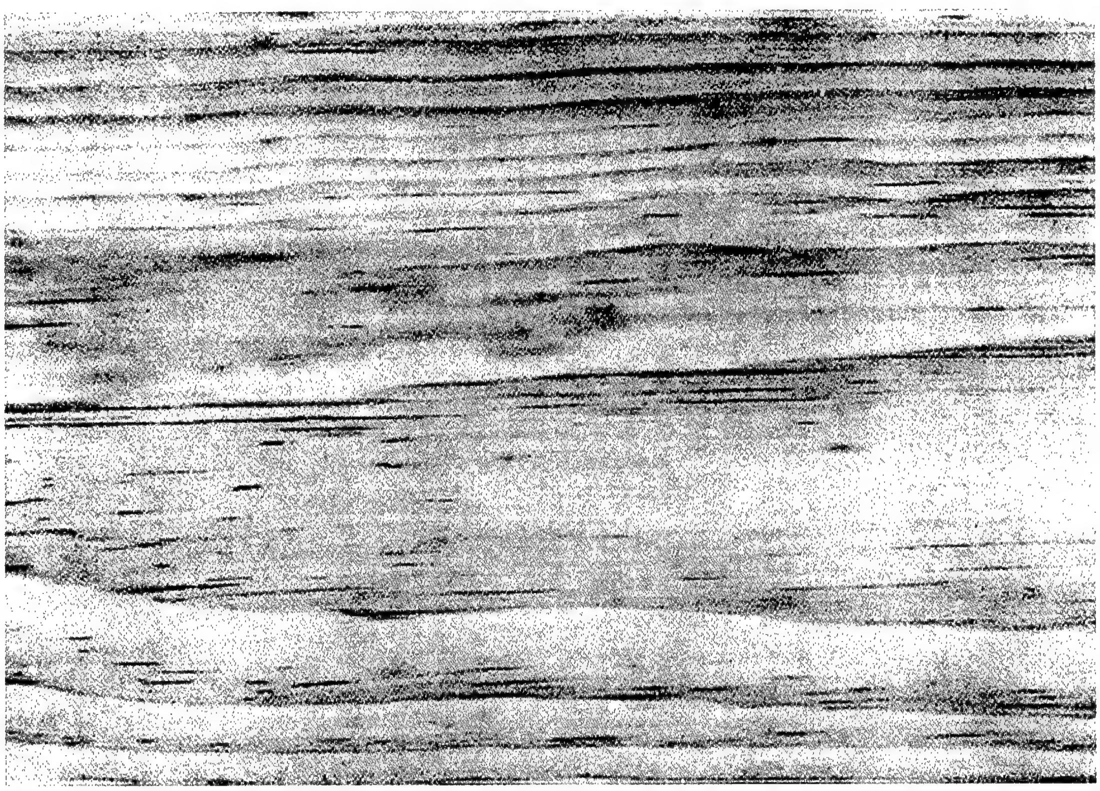


Figure 10. Western White Pine, flat-cut cross-section.

2.7.7 Redwood

Other names: Coast Redwood, California Redwood, Sequoia.

Location: Coast of California. (A related species — giant sequoia — grows in a limited area in the Sierra Nevada of California, but is used in very limited quantities.)

Production: Limited to California, but used nationwide.

Use: Although produced exclusively in California, the species is used nationwide in construction. Due to its high durability, it is useful for cooling towers, tanks, silos, wood-stave pipe, and outdoor furniture. It also is used in agriculture for buildings and equipment; its use as timbers and large dimension stock in bridges and trestles is relatively rare.

Density: 400 kg/m^3 (25 lb/ft^3).

Strength: Moderately strong for its weight but not as strong as the general run of constructional softwoods.

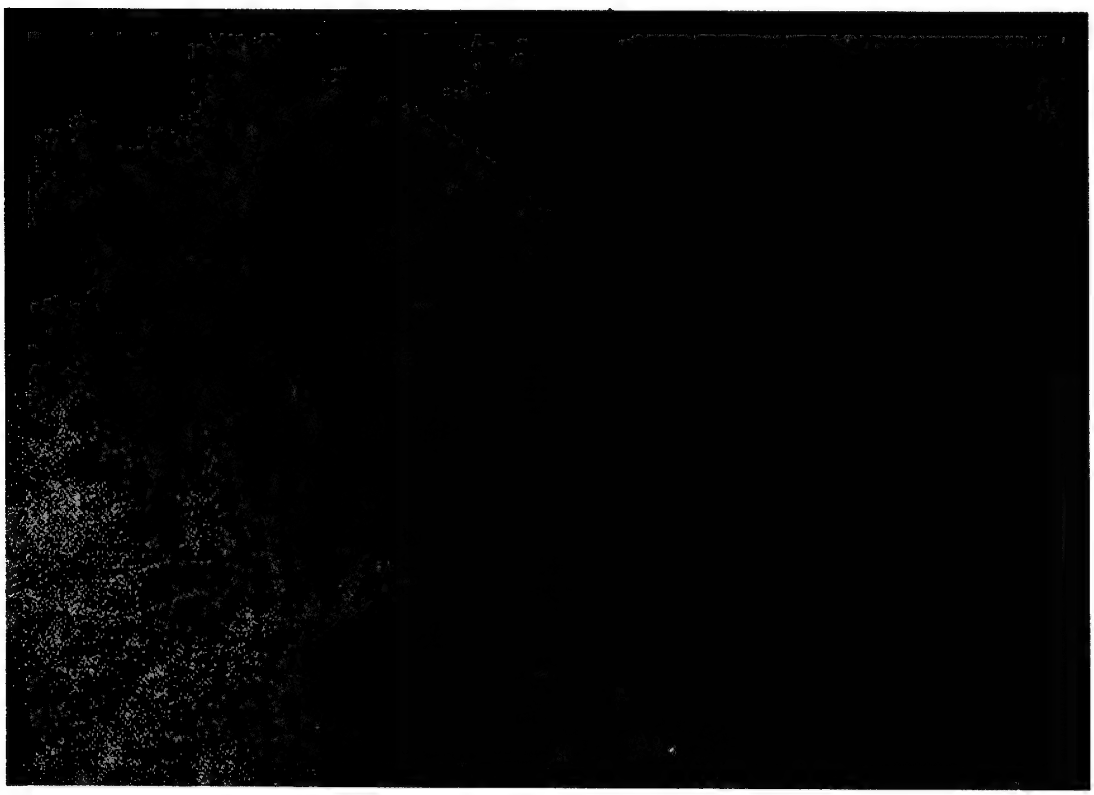


Figure 11. Redwood, flat-cut cross-section.

2.7.8 Engelmann Spruce (ES)

Other names: White Spruce, Mountain Spruce, Arizona Spruce, Silver Spruce, Balsam.

Location: Grows at high elevations in the Rocky Mountain region of the United States. Approximately two-thirds of the lumber is produced in the southern Rocky Mountain States; most of the remainder comes from the northern Rocky Mountain States and Oregon.

Use: Principally for lumber and for mine timbers, railroad ties, and poles; it is used also in building construction in the form of dimension stock, flooring, sheathing, and studding.

Density: 350 kg/m^3 (22 lb/ft^3).

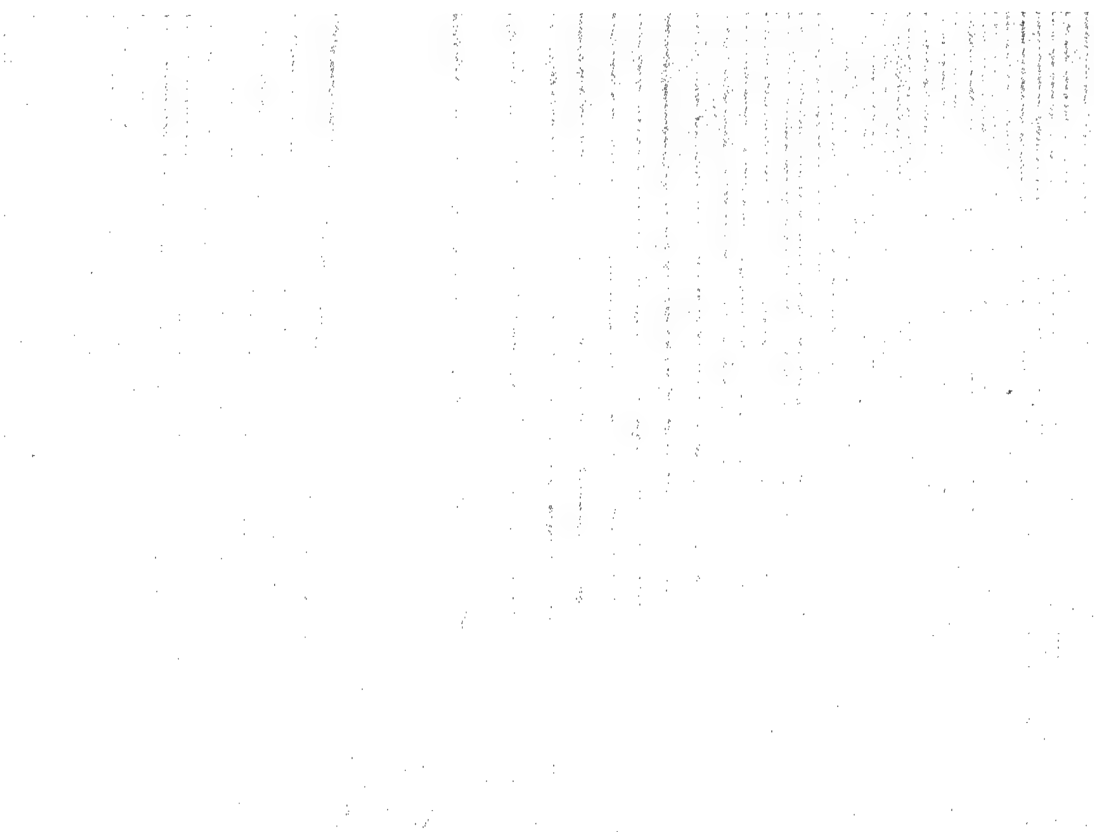


Figure 12. Engelmann Spruce, flat-cut cross-section.

2.8 Other Commercially Used Softwoods

2.8.1 True Fir (Eastern Species)

Other names: Balsam Fir, Canadian Fir, White Fir.

Location: Grows principally in New England, Pennsylvania, and the Lake States.

Use: Used mainly for pulpwood, but some lumber is produced for light duty uses.

Density: 350 kg/m^3 (22 lb/ft^3).

Strength: Rated as light in weight, low in bending and compressive strength, moderately limber, soft, and low in resistance to shock.

2.8.2 Western True Fir (WF)

Other names: Sub-Alpine Fir, California Red Fir, Grand Fir, Noble Fir, Pacific Silver Fir, White Fir.

Location: Washington, Oregon, California, western Montana, and northern Idaho.

Use: Lumber goes principally into building construction, boxes and crates, planing mill products, sash, doors, and general millwork; in house construction, the lumber is used for framing, subflooring, and sheathing.

Density: 390 kg/m^3 (24 lb/ft^3).

2.8.3 Eastern Hemlock (HEM)

Other names: Canadian Hemlock, Hemlock Spruce, American Hemlock, Spruce Pine.

Location: Grows from New England to northern Alabama and Georgia, and in the Great Lakes States.

Production: New England States, the middle Atlantic States, and the Great Lakes States.

Use: Principally for lumber and pulpwood; the lumber is used largely in building construction for framing, sheathing, subflooring, and roof boards, and in the manufacture of boxes, pallets, and crates.

Density: 400 kg/m^3 (25 lb/ft^3).

2.8.4 Western Larch (L)

Other names: n/a

Location: Grows in western Montana, northern Idaho, northeastern Oregon, and on the eastern slope of the Cascade Mountains in Washington. Approximately two-thirds of the lumber is produced in Idaho and Montana, and one-third in Oregon and Washington.

Use: Mainly in building construction for rough dimension, small timbers, planks and boards, and for railroad ties and mine timbers.

Density: 520 kg/m^3 (32 lb/ft^3).

Durability: Very strong for a softwood and it is also moderately durable against the attack of wood-rotting fungi.

2.8.5 Sugar Pine (SP)

Other names: California Sugar Pine.

Location: California and southwestern Oregon.

Use: Entirely for lumber products; the largest amounts are used in boxes and crates, sash, doors, frames, blinds, general millwork, building construction, and foundry patterns; suitable for use in nearly every part of a house because of the ease with which it can be cut, its ability to stay in place, and its good nailing properties.

Density: 360 kg/m^3 (22 lb/ft^3).

Strength: Low in strength compared with other commercial species of pine.

Durability: Not durable; moderately resistant to preservative treatment.

3 Grading Concepts and Procedures

Grading is based on certain rules that take into consideration defects, such as knots (intergrown, loose), resin pockets, compression or tension wood, checks, spiral grain, discolorations, and wane (defective dimensions). The rules vary in different species and countries, and the importance of defects is weighed differently in softwoods and in hardwoods.

Softwood grading is based on a defect system that accounts for the number and size of defects. Dimensions are also important. Further processing to final products is not taken into consideration, although the removal of edge defects can substantially change the grade. Lumber produced in northwest North America (United States and Canada) is classified into seven grades. The organizations promoting softwood grades are shown in Table 2 for the various softwoods used in building construction. Table 3 presents a general description of the commercial species of softwood lumber available, along with their structural characteristics.

Softwood lumber grades can be considered in the context of two major categories of use: construction and remanufacture. The term *construction* relates principally to lumber expected to function as graded and sized after primary processing (sawing and planing). The term *remanufacture* refers to lumber that will undergo a number of further manufacturing steps and reach the consumer in a significantly different form.

The grading requirements of construction lumber are related specifically to the major construction uses intended, and little or no more grading occurs once the piece leaves the sawmill. Construction lumber can be placed in three general categories: stress-graded, nonstress-graded, and appearance lumber. *Stress-graded* and *nonstress-graded* lumber are used where the structural integrity of the piece is the primary requirement. *Appearance lumber* encompasses products in which appearance is of primary importance; structural integrity, while sometimes important, is a secondary feature.

3.1 Stress-Graded Lumber

Almost all softwood lumber nominally 2 to 4 in. thick (dimension lumber) is stress-graded and assigned allowable properties under the National Grading Rule (NGR), a part of the American Softwood Lumber Standard (Department of Commerce Voluntary Product Standard [DOC PS] 20-99). A single set of grade names and descriptions is used throughout the United States although the allowable properties vary with species. Other stress-graded products include timbers, posts, stringers, beams, decking, and some boards. Grades are based on strength ratios that are established by experimental means. The grade designation for mechanically or machine stress-rated (MSR) lumber includes an E rating (modulus of elasticity).

Dimension lumber is the principal stress-graded lumber item available in a retail yard. It is primarily framing lumber for joists, rafters, and studs. Strength, stiffness, and uniformity of size are essential requirements.

3.2 Nonstress-Graded Lumber

In nonstress-graded structural lumber, the section properties (shape, size) of the pieces combine with the visual grade requirements to provide the degree of structural integrity intended. Boards are the most important nonstress-graded product. They are separated into three to five different grades, depending upon the species and lumber manufacturing association involved. The top-grade boards are usually graded primarily for serviceability, but appearance is also considered. This grade is used for siding, cornice, shelving, and paneling. Features such as knots and knotholes are permitted to be larger and more frequent as the grade level becomes lower. Intermediate-grade boards are often used for such purposes as subfloors, roof and wall sheathing, and rough concrete work. The lower grade boards are not selected for appearance but for adequate strength. They are used for roof and wall sheathing, subfloor, and rough concrete form work.

3.3 Appearance Lumber

Appearance lumber often is nonstress-graded, but it forms a separate category because of the distinct importance of appearance in the grading process. This category of construction lumber includes most lumber that is machined to a pattern. The appearance category includes trim, siding, flooring, ceiling, paneling, casing, base, stepping, and finish boards. Appearance grades emphasize the quality of one face;

the reverse side may be lower in quality. Appearance grades are not uniform across species and products, and official grade rules must be used for detailed reference.

Table 2. Organizations promulgating softwood grades.

Name and address	Phone & Fax	Species covered by grading rules
California Lumber Inspection Service 1305 N. Bascom Ave., Suite J Box 6989 San Jose, California 95150	Ph. (408) 241-2960 Fax (408) 246-5415	Douglas Fir
Northeastern Lumber Manufacturers Association, Inc. 272 Tuttle Road, P.O. Box 87A Cumberland Center, Maine 04021	Ph. (207) 829-6901 Fax (207) 829-4293	Balsam fir, eastern white pine, red pine, eastern hemlock, white spruce, red spruce, pitch pine, northern white pine
Northern Softwood Lumber Bureau 272 Tuttle Road, P.O. Box 87A Cumberland Center, Maine 04021	Ph. (207) 829-6901 Fax (207) 829-4293	Balsam fir
Pacific Lumber Inspection Bureau, Inc. P.O. Box 7235 Bellevue, Washington 98008-1235	Ph. (206) 746-6542 Fax (206) 746-5522	Hemlock firs
Redwood Inspection Service 405 Enfrente Drive, Suite 200 Navato, California 94949	Ph. (415) 382-0662 Fax (415) 382-8531	Redwood
Renewable Resource Associates, Inc. 3091 Chaparral Place Lithonia, Georgia 30038	Ph. (404) 482-9385 Fax (404) 482-9385	Baldcypress
Southern Pine Inspection Bureau 4709 Scenic Highway Pensacola, Florida 32504	Ph. (904) 434-2611 Fax (904) 434-5594	Longleaf pine, pitch pine
Timber Products Inspection P.O. Box 919 Conyers, Georgia 30207	Ph. (404) 922-8000 Fax (404) 922-1290	Baldcypress
West Coast Lumber Inspection Bureau Box 23145 6980 SW Varns Road Portland, Oregon 97223	Ph. (503) 639-0651 Fax (503) 684-8928	Douglas Fir, western hemlock, western true firs
Western Wood Products Association Yeon Building 522 SW Fifth Avenue Portland, Oregon 97204-2122	Ph. (503) 224-3930 Fax (503) 224-3934	Western white pine, Douglas Fir, sugar pine, western true firs, western larch, Engelmann spruce, western hemlock

Table 3. Commercial species of softwood lumber.

Species Combination	Abbr.	Species Included in Combination	Characteristics	Color Ranges
Douglas Fir-Larch	DF-L or D.Fir-L	Douglas Fir, Western larch	high degree of hardness good resistance to decay	reddish brown to yellowish
Hem-Fir	H-F or Hem-Fir	Pacific coast hemlock, Amabilis fir	works easily takes paint well holds nails well good gluing characteristics	yellow brown to white
Spruce-Pine-Fir	S-P-F	Spruce (all species except coast sitka spruce), Jack pine, Lodgepole pine, Balsam fir, Alpine fir	works easily takes paint well holds nails well	red cedar: reddish brown heartwood, light sapwood
Northern Species	Nor or North	Red pine	works easily	pale yellow color sapwood
		Ponderosa pine	takes finish well holds nails well holds screws well seasons with little checking or cupping	creamy white to light straw brown heartwood, almost white sapwood
		Western white pine, Eastern white pine	softest of pines works easily finishes well does not tend to split or splinter holds nails well low shrinkage takes stains, paints, varnishes well	

3.4 Visual Grading

Visual grading is the oldest stress-grading method. It is based on the premise that mechanical properties of lumber differ from mechanical properties of clear wood because there are many growth characteristics that affect properties and can be seen and judged by eye. These growth characteristics are typical visual sorting criteria.

3.4.1 Density

Strength is related to the weight per unit volume (density) of clear wood. Properties assigned to lumber are sometimes modified by using the rate of growth and the percentage of latewood as measures of density. Typically, selection for density requires that the number of annual rings per inch and the percent latewood be within a specified range.

3.4.2 Decay

Decay in most forms should be prohibited or severely restricted in stress grades because the degree of decay is difficult to determine and its effects on strength is often greater than visual observation would indicate.

3.4.3 Heartwood and Sapwood

Heartwood and sapwood of the same species have equal mechanical properties, and no requirement need be made in stress grading. Because heartwood of some species is more resistant to decay than sapwood, heartwood may be required if the untreated wood is to be exposed to a decay hazard. On the other hand, sapwood takes preservative treatment more readily and is preferred in lumber that is to be treated.

3.4.4 Slope of Grain

Slope of grain (cross grain) reduces the mechanical properties of lumber because the fibers are not parallel to the edges. Severely cross-grained pieces are also undesirable because they tend to warp with changes in moisture content. Stresses caused by shrinkage during drying are greater in structural lumber than in small, clear specimens and are increased in zones of sloping or distorted grain.

Elastic properties in directions other than along the natural axes can be obtained from elastic theory. Strength properties in directions ranging from parallel to perpendicular to the fibers can be approximated using a Hankinson-type formula:

$$N = \frac{PQ}{P \sin^n \theta + Q \cos^n \theta}$$

where:

N = strength property at an angle θ from the fiber direction
Q = strength perpendicular to the grain
P = strength parallel to the grain
n = empirically determined constant

The formula has been used for modulus of elasticity as well as strength properties. Values of n and associated ratios of Q/P shown in Table 4 are compiled from available literature.

Table 4. Representative value ranges for n and Q/P ratios.

Property	*n*	*Q/P*
Tensile strength	1.5–2.0	0.04–0.07
Compressive strength	2.0–2.5	0.03–0.4
Bending strength	1.5–2.0	0.04–0.1
Modulus of elasticity	2.0	0.04–0.12
Toughness	1.5–2.0	0.06–0.1

3.4.5 Knots and Checks

Knots cause localized cross grain with steep slopes. One of the most damaging aspects of knots in sawn lumber is that the continuity of the grain around the knot is interrupted by the sawing process. In general, knots have a greater effect on strength in tension than compression. The effect of a knot on strength depends approximately on the proportion of the cross-section of the piece of lumber occupied by the knot as well as knot location and distribution of stress in the piece.

The adverse effect of knots is mainly due to local grain deviations and checks caused by their presence. Checks are formed due to differential shrinkage and swelling of knots, because knot density is higher and fiber orientation is different than the adjacent wood. Intergrown (tight) knots cause greater deviations and more checking, whereas encased (loose) ones act, in addition, through absence of material or discontinuity of tissues. The presence of knots greatly reduces the strength of wood in axial tension due to associated grain deviations. The transverse tensile strength is very low in comparison to axial strength. Strength in axial compression is reduced less, whereas strength in transverse compression may increase by the presence of intergrown knots. Bending strength (modulus of rupture) is considerably influenced by the position of knots.

Knots found near the middle of the lower side of simple beams supported at both ends have the greatest adverse effect. Strength in horizontal shear is slightly affected or not at all, or it may increase, because knots interrupt the continuity of checks, which greatly reduce this strength. The influence of checks depends on their size, direction, and the manner of loading. Axial tensile strength is unaffected or slightly affected when checks have the same direction with the forces exerting tension. Inversely, transverse tensile strength is greatly reduced. The effect of checks on compressive strength is smaller in transverse than axial compression, but the reduction of strength in horizontal shear is considerable. It is evident that in loading of beams, the influence is greater when checks are near the neutral plane,

where horizontal shear stresses are greatest. Checks usually coexist with grain deviations and knots.

3.4.6 Shake

Shake is a separation or a weakness of fiber bond between annual rings that is presumed to extend lengthwise without limit. In members subjected to bending, shake reduces the resistance to shear. Therefore, grading rules restrict shake most closely in those parts of a bending member where shear stresses are highest. In members subjected only to tension or compression, shake does not greatly affect strength. Shake may be limited in a grade because of appearance and because it permits entrance of moisture that results in decay.

3.5 Mechanical Grading

Basic procedures and protocols for grading wood according to its mechanical properties are outlined below. Chapter 4, section 4.2 presents more detail on wood testing configurations used in mechanical grading and provides specific property information for 13 common softwood species under various content conditions.

3.5.1 Procedures for Deriving Mechanical Properties

The mechanical properties of visually graded lumber may be established by either:

1. appropriate modification of test results conducted on small, clear specimens (small clear procedure)
2. testing a representative sample of full-size members (in-grade testing procedure).

3.5.1.1 Small Clear Procedure

Sorting criteria that influence mechanical properties are handled with strength ratios for strength properties and with quality factors for the modulus of elasticity. Once the clear wood properties have been modified for the influence of sorting criteria and variability of wood properties and occurrence of the growth characteristics, additional modifications for size, moisture content, safety, and load duration are applied.

3.5.1.2 In-Grade Testing Procedure

To establish the mechanical properties of specified grades of lumber from tests of full-size specimens, a representative sample of the lumber population is obtained following guidelines given in ASTM D 2915. Hence, an average value for the modulus of elasticity or a near-minimum estimate of strength properties is obtained. The specimens are then tested using appropriate procedures such as those given in ASTM D 198. The properties are further modified for design use by consideration of moisture content, duration of load, and safety.

3.5.2 Basic Mechanical Grading Protocol

The mechanical stress rating (MSR) for lumber is based on an observed relation between modulus of elasticity and bending strength. The modulus of elasticity is the sorting criterion used in this method of grading. Mechanical devices operating at high speeds measure the modulus of elasticity of individual pieces of lumber. The three basic components of MSR systems used in the United States and Canada are:

1. mechanical sorting and prediction of strength through a machine-measured non-destructive determination of the modulus of elasticity
2. assignment of allowable design stresses based upon strength predictions
3. quality control procedures to assure:
   (a) proper operation of the machine used to measure the modulus of elasticity
   (b) the appropriateness of the predictive parameter-bending strength relationship
   (c) the appropriateness of properties assigned for tension and compression (properties not directly related to the modulus of elasticity).

4 Structural Properties of Wood

4.1 Softwood Lumber Manufacture

Standards for lumber size, grade, and properties are established and maintained by the American Lumber Standard Committee (ALSC), an independent body whose members are appointed by the U.S. Department of Commerce to represent producers, specifiers, and consumers of softwood lumber. Voluntary Product Standards (PS), grading rules, etc., developed through ALSC are published by the Department of Commerce.

4.1.1 Size

Lumber length is recorded in actual dimensions, while width and thickness are traditionally recorded in nominal dimensions, that are somewhat larger than the actual dimensions. Softwood lumber is manufactured in length multiples of 1 foot as specified in various grading rules. Table 5 presents the American standard lumber sizes for stress-graded and nonstress-graded lumber for construction. In practice, two-foot multiples (in even numbers) are the rule for most construction lumber. Width of softwood lumber varies, commonly 2 – 16 in. nominal. The thickness of lumber can be generally categorized as follows:

- *Boards*: lumber less than 2 in. in nominal thickness
- *Dimension*: lumber from 2 in. up to, but not including, 5 in. in nominal thickness
- *Timbers*: lumber 5 in. or more in nominal thickness in the smallest dimension.

4.1.2 Surfacing

Lumber can be produced either rough or surfaced. Rough lumber has surface imperfections caused by the primary sawing operations. Surfaced lumber has been planed or sanded on either side or both. Surfacing may be done to attain smoothness, or uniformity of size, or both.

Table 5. American standard lumber sizes for stress-graded and nonstress-graded lumber.

Item	Thickness (in.)			Face width (in.)		
	Nominal	Minimum dressed		Nominal	Minimum dressed	
		Dry	Green		Dry	Green
	in.			in.		
Boards	1	¾	25/32	2	1 ½	1 9/16
	1 ¼	1	1 1/32	3	2 ½	2 9/16
	1 ½	1 ¼	1 9/32	4	3 ½	3 9/16
				5	4 ½	4 5/8
				6	5 ½	5 5/8
				7	6 ½	6 5/8
				8	7 ¼	7 ½
				9	8 ¼	8 ½
				10	9 ¼	9 ½
				11	10 ¼	10 ½
				12	11 ¼	11 ½
				14	13 ¼	13 ½
				16	15 ¼	15 ½
Dimension	2	1 ½	1 9/16	2	1 ½	1 9/16
	2 ½	2	2 1/16	3	2 ½	2 9/16
	3	2 ½	2 9/16	4	3 ½	3 9/16
	3 ½	3	3 1/16	5	4 ½	4 5/8
	4	3 ½	3 9/16	6	5 ½	5 5/8
	4 ½	4	4 1/16	8	7 ¼	7 ½
				10	9 ¼	9 ½
				12	11 ¼	11 ½
				14	13 ¼	13 ½
				16	15 ¼	15 ½
Timbers	5 and greater		½ less than nominal	5 and greater		½ less than nominal

4.2 Principal Mechanical Properties

The mechanical properties presented in Tables 6 – 8 are based on extensive sampling of a number of softwood species grown in North America. The properties are represented as the average mechanical properties of the species and are used to determine allowable values for design. Wood characteristics vary considerably, even in clear material on which most tests are based. These tables present information on the nature and magnitude of this variability in mechanical properties.

The speed of sound propagation through wood is a useful metric because it correlates to a specimen's modulus of elasticity. The speed of sound varies depending on direction of propagation (axial, transverse) and species of wood. Transversely, the speed is lower due to the higher modulus of elasticity; sound speed across the grain is about 20 – 33 percent — and sometimes as little as 5 percent — of the longitudi-

nal value. The speed of sound is calculated as the square root of the quantity of modulus of elasticity divided by oven-dry density or specific gravity. Table 6 presents the speed of sound in the longitudinal direction for the various species.

Table 6. Density and shrinkage* (air-dry density, 12 – 15 percent moisture content and total shrinkage from green to zero-moisture content).

Species	Density lb/ft^3 (g/cm^3)		Speed of Sound**	Shrinkage (%)		
	Air-dry	Green	(in./sec)	Radial	Tangential	Volumetric
Southern Cypress	29 (0.46)	26 (0.42)	182,000	3.8	6.2	10.5
Douglas Fir	30 (0.48)	28 (0.45)	208,000	4.8	7.6	12.4
Eastern true fir	22 (0.35)	21 (0.33)	210,000	2.9	6.9	11.2
Western true fir	24 (0.39)	23 (0.37)	204,000	3.3	7.0	9.8
Eastern Hemlock	25 (0.40)	24 (0.38)	179,000	3.0	6.8	9.7
Western Hemlock	28 (0.45)	26 (0.42)	198,000	4.2	7.8	12.4
Western Larch	32 (0.52)	30 (0.48)	198,000	4.5	9.1	14.0
Longleaf pine	37 (0.59)	34 (0.54)	189,000	5.1	7.5	12.2
Red pine	29 (0.46)	26 (0.41)	194,000	3.8	7.2	11.3
Sugar pine	22 (0.36)	21 (0.34)	190,000	2.9	5.6	7.9
Western white pine	24 (0.38)	22 (0.35)	202,000	4.1	7.4	11.8
Redwood	25 (0.40)	24 (0.38)	189,000	2.6	4.4	6.8
Engelmann spruce	22 (0.35)	21 (0.33)	199,000	3.8	7.1	11.0

* Reference: *Wood Handbook: Wood as an Engineering Material*, United States Department of Agriculture, Forest Service, Agriculture Handbook 72, 1987.

**Calculation of the speed of sound was based on the air-dry density due to lack of information on oven-dry density.

Table 7. Mechanical properties at dry conditions.

Species	Tension*		Compression*		Static bending		Shear	Hardness (side)	Toughness	
	||	⊥	||	⊥	MOR[2]	MOE[3]			R[4]	T[5]
	psi							lb	in.-lb	
Southern Cypress		270	6,360	730	10,600	1.44×10^6	1,000	510		
Douglas Fir	18,900	340	7,240	800	12,400	1.95×10^6	1,130	710	200	360
Eastern true fir		180	5,280	404	9,200	1.45×10^6	944	400		
Western true fir		300	5,800	530	9,800	1.50×10^6	1,100	480	130	200
Eastern Hemlock			5,410	650	8,900	1.20×10^6	1,060	500		
Western Hemlock		340	7,130	550	11,300	1.64×10^6	1,250	540	140	210
Western Larch	19,400	430	7,640	930	13,100	1.87×10^6	1,360	830	210	340
Longleaf pine		470	8,470	960	14,500	1.98×10^6	1,510	870		
Red pine		460	6,070	600	11,000	1.63×10^6	1,210	460	160	290
Sugar pine		350	4,460	500	8,200	1.19×10^6	1,130	380		
Western white pine			5,040	470	9,700	1.46×10^6	1,040	420		
Redwood		240	6,150	700	10,000	1.34×10^6	940	480	90	140
Engelmann spruce	13,000	350	4,480	410	9,300	1.30×10^6	1,200	390	110	180

* | | is parallel to grain; ⊥ is perpendicular to grain.

1 Data based on small, clear specimens in air-dry condition.

2 Modulus of rupture

3 Modulus of elasticity

4 Indicates load applied to radial face

5 Indicates load applied to tangential face

Table 8. Mechanical properties at green conditions[1].

Species	Tension*		Compression*		Static bending		Shear	Hardness (side)	Toughness	
	$\parallel$	$\perp$	$\parallel$	$\perp$	MOR[2]	MOE[3]			R[4]	T[5]
	psi							lb	in.-lb	
Southern Cypress		300	3,580	400	6,600	1.18×10^6	810	390		
Douglas Fir		300	3,780	380	7,700	1.56×10^6	900	500	210	360
Eastern true fir		180	2,630	190	5,500	1.25×10^6	662	290		
Western true fir		300	2,900	280	5,900	1.16×10^6	760	340	140	220
Eastern Hemlock		230	3,080	360	6,400	1.07×10^6	850	400		
Western Hemlock		290	3,360	280	6,600	1.31×10^6	860	410	150	170
Western Larch		330	3,760	400	7,700	1.46×10^6	870	510	270	400
Longleaf pine		330	4,320	480	8,500	1.59×10^6	1,040	590		
Red pine		300	2,730	260	5,800	1.28×10^6	690	340	210	350
Sugar pine		270	2,460	210	4,900	1.03×10^6	720	270		
Western white pine		260	2,430	190	4,700	1.19×10^6	680	260		
Redwood		260	4,200	420	7,500	1.18×10^6	800	410	110	200
Engelmann spruce		240	2,180	200	4,700	1.03×10^6	640	260	150	190

* $\parallel$ is parallel to grain; $\perp$ is perpendicular to grain.
[1] Data based on small, clear specimens in air-dry condition.
[2] Modulus of rupture
[3] Modulus of elasticity
[4] Indicates load applied to radial face
[5] Indicates load applied to tangential face

Table 9. Effect of moisture content on strength properties[1].

Species	Tension*		Compression*		Static bending		Shear	Hardness (side)	Toughness	
	$\parallel$	$\perp$	$\parallel$	$\perp$	MOR[2]	MOE[3]			R[4]	T[5]
	% increase of air-dry over green values									
Southern Cypress		-11.1	43.7	45.2	37.7	18.1	19.0	23.5		
Douglas Fir		11.8	47.8	52.5	37.9	20.0	20.4	29.6	-5.0	0.0
Eastern true fir		0.0	50.2	53.0	40.2	13.8	29.9	27.5		
Western true fir		0.0	50.0	47.2	39.8	22.7	30.9	29.2	-7.7	-10.0
Eastern Hemlock			43.1	44.6	28.1	10.8	19.8	20.0		
Western Hemlock		14.7	52.9	49.1	43.4	20.1	31.2	24.1	-7.1	19.0
Western Larch		23.3	50.8	57.0	41.2	21.9	36.0	38.6	-28.6	-17.6
Longleaf pine		29.8	49.0	50.0	41.4	19.7	31.1	32.2		
Red pine		53.3	55.0	56.7	47.3	21.5	43.0	26.1	-31.3	-20.7
Sugar pine		22.9	44.8	58.0	40.2	13.4	36.3	28.9		
Western white pine			51.8	59.6	51.5	18.5	34.6	38.1		
Redwood		-8.3	31.7	40.0	25.0	11.9	14.9	14.6	-22.2	-42.9
Engelmann spruce		31.4	51.3	51.2	49.5	20.8	46.7	33.3	-36.4	-5.6

* $\parallel$ is parallel to grain; $\perp$ is perpendicular to grain.
[1] Data based on small, clear specimens in air-dry condition.
[2] Modulus of rupture
[3] Modulus of elasticity
[4] Indicates load applied to radial face
[5] Indicates load applied to tangential face

The following illustrations and pictures (Figures 13–19) represent the various testing configurations for clear wood specimens. These configurations are designed to obtain the most significant strength properties associated with the structural behavior of wood. The shapes illustrated in Figure 13 — especially items (b) and (c) — are representative of ASTM standards.

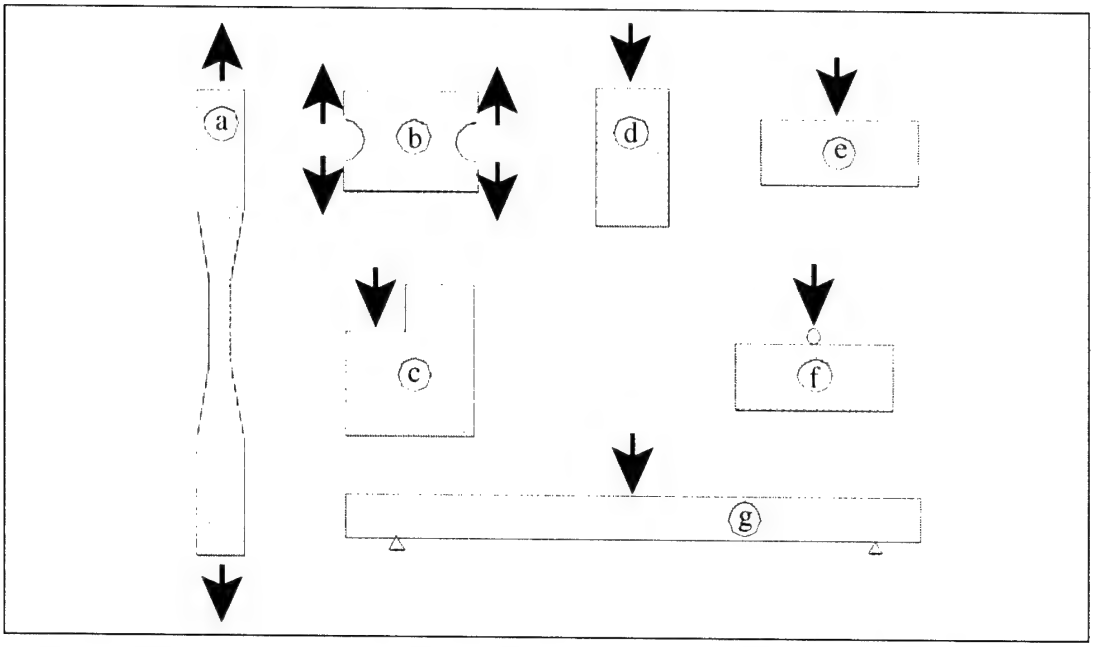


Figure 13. Specimen shapes and loads for determining the mechanical properties of wood: (a) axial tension, (b) transverse tension, (c) shear, (d) axial compression, (e) transverse compression, (f) side hardness, and (g) static bending.

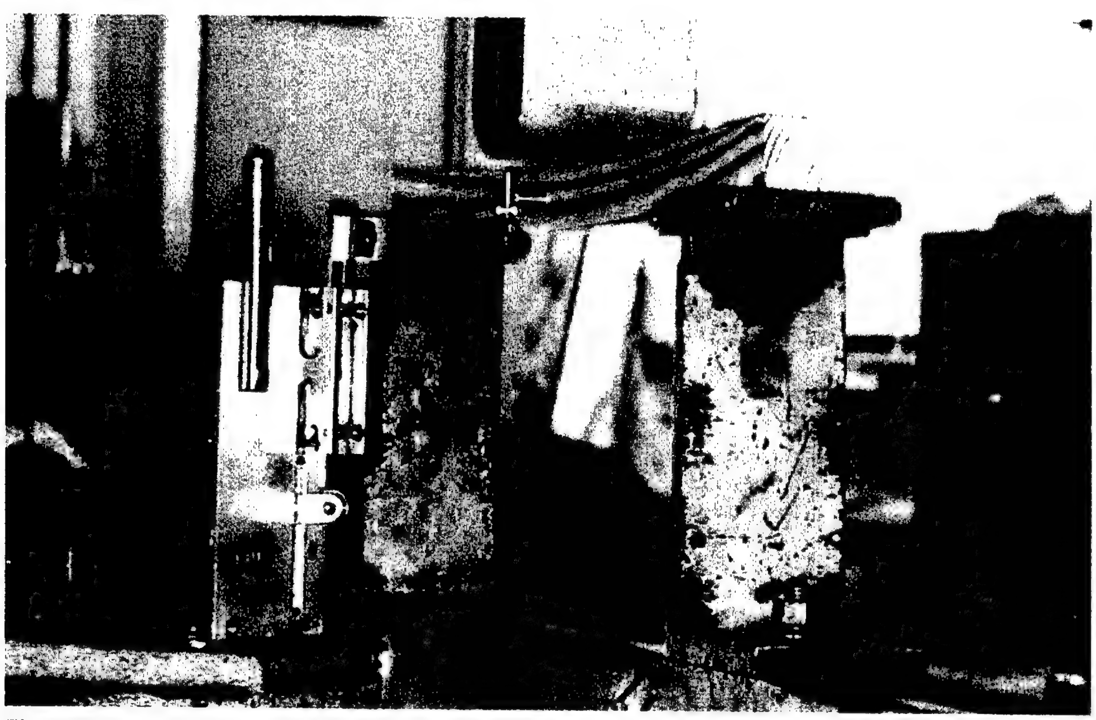


Figure 14. Static bending test.

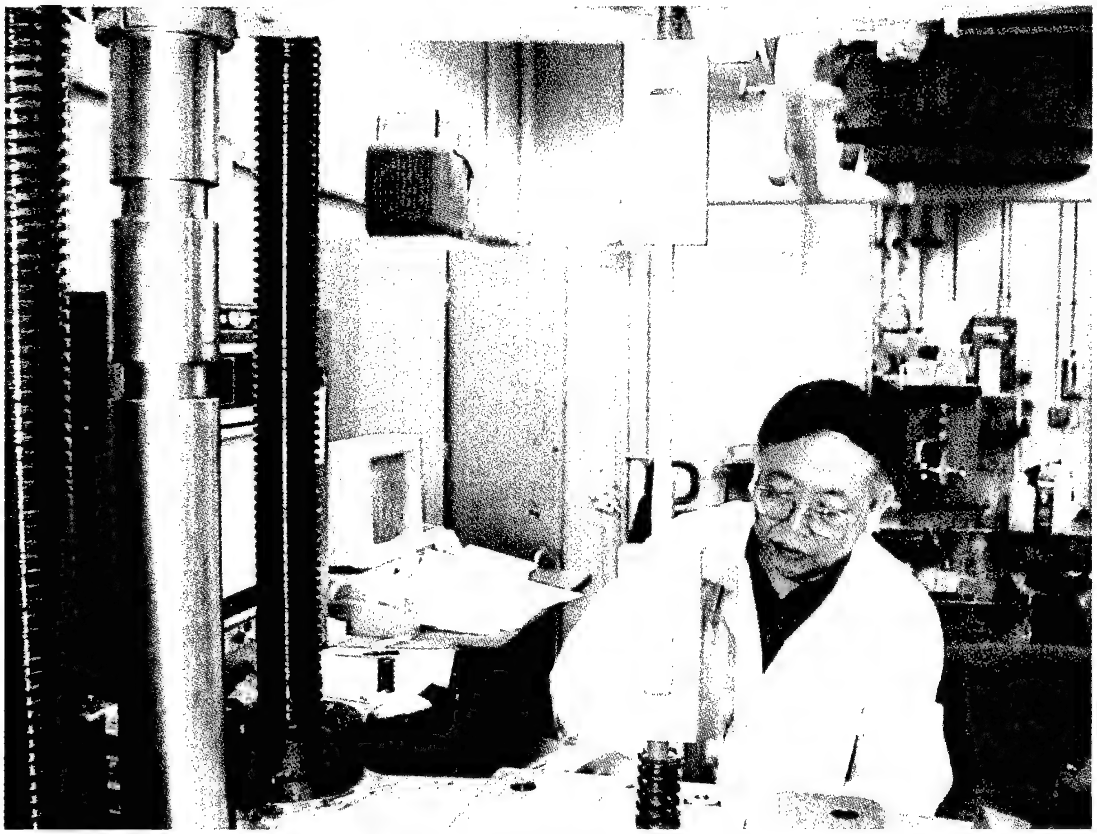


Figure 15. Axial tension test.

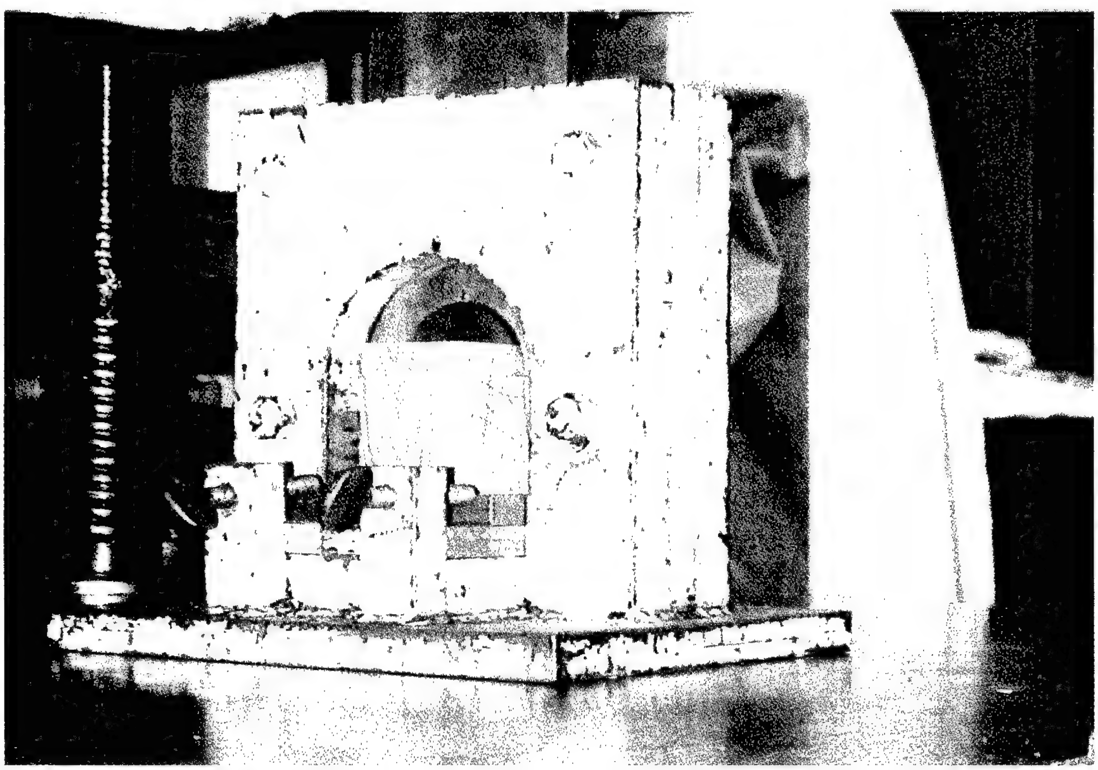


Figure 16. Axial shear test.

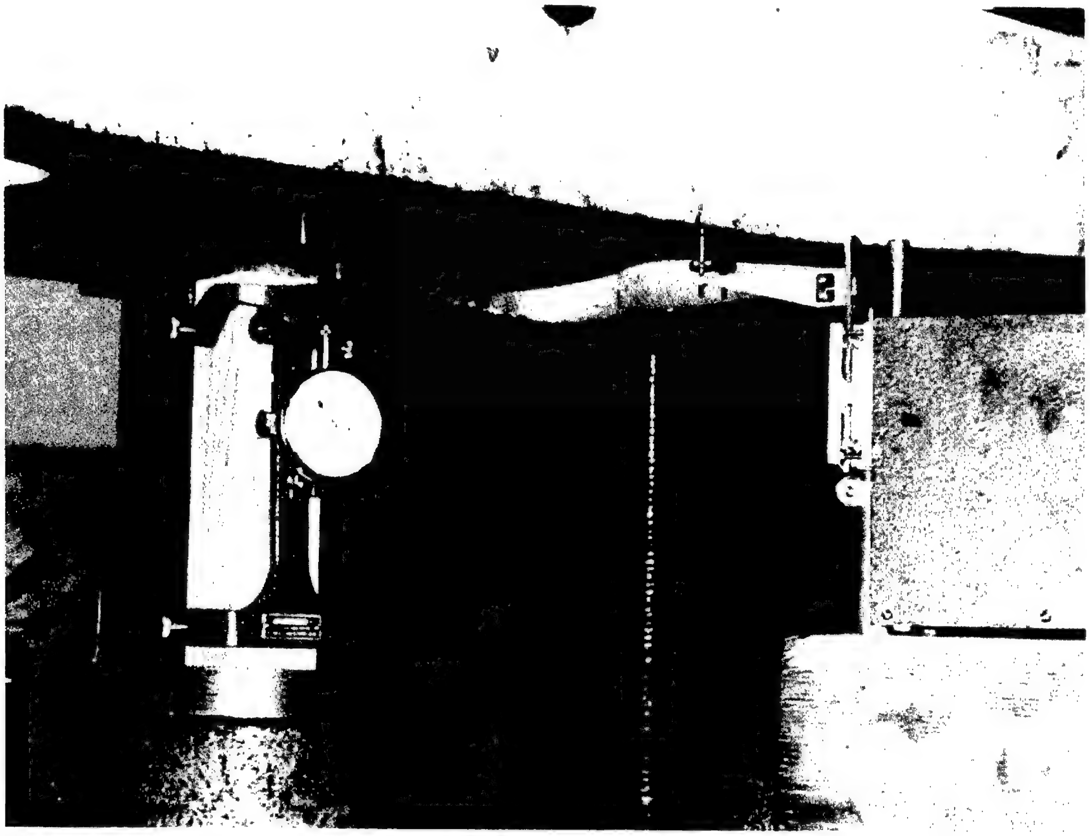


Figure 17. Axial compression test with deformation gauge.

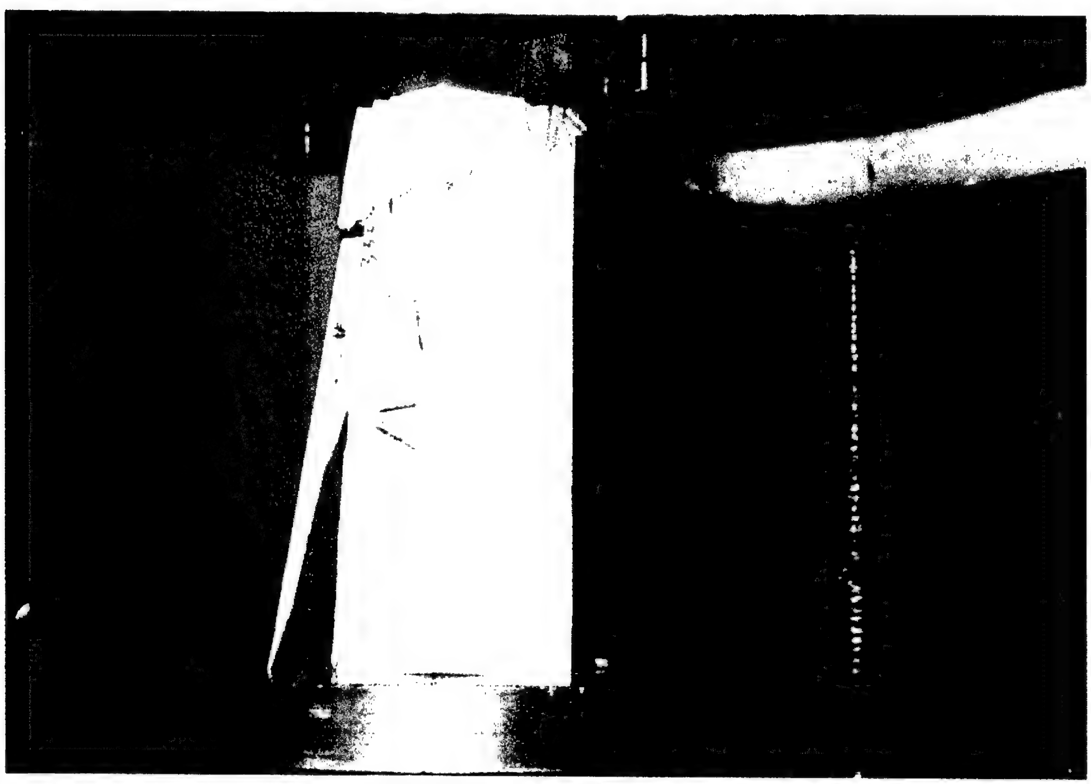


Figure 18. Typical failure for axial compression test.

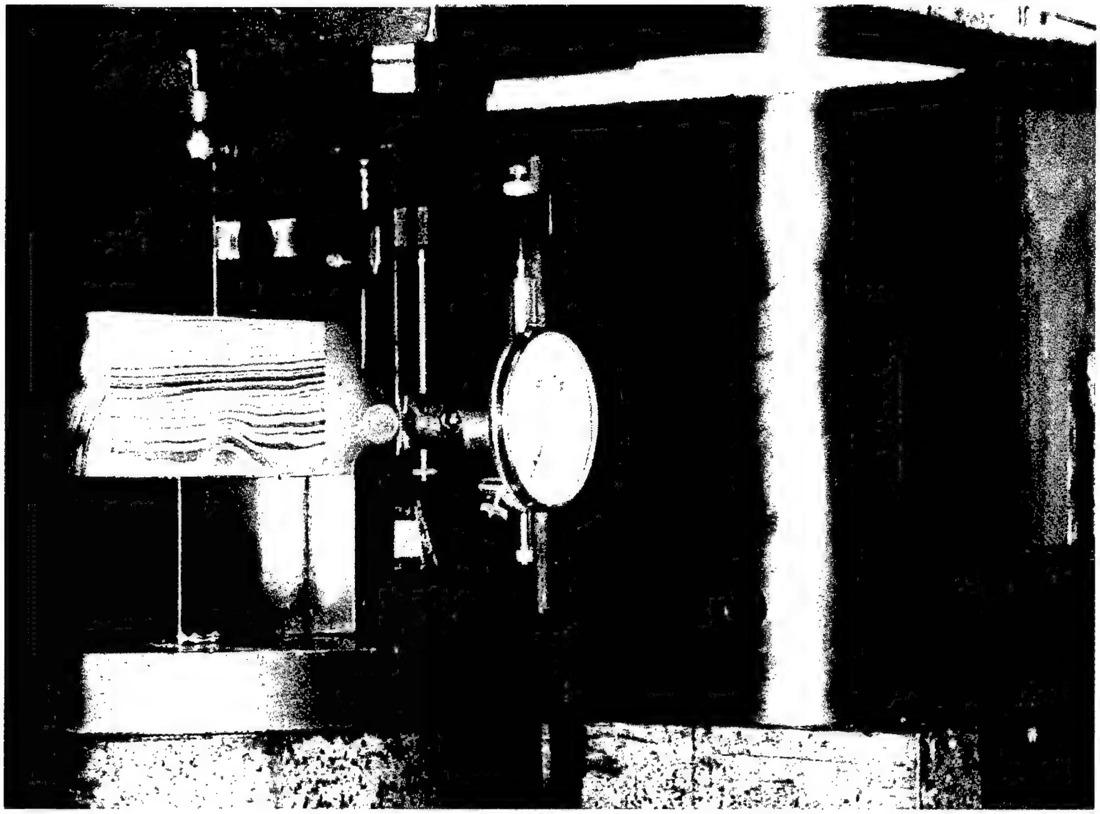


Figure 19. Transverse compression test.

Strength in tension (axial or transverse) is determined from the relationship:

$$S = \frac{P}{A}$$

where:

S = ultimate stress in axial (or transverse) tension (psi)
P = ultimate load (lb)
A = minimum cross-section of the specimen (in.^{2})

Tests of axial compression give the following properties:

a. *Proportional fiber stress in axial compression* from the relationship:

$$S' = \frac{P'}{A}$$

where:

S' = stress at proportional limit (psi)
P' = load at proportional limit (lb)
A = cross-section of the specimen (in.^{2})

b. *Modulus of elasticity in axial compression* from the relationship:

$$E = \frac{P'L}{AD}$$

where:

E = modulus of elasticity (psi)
P' = load at proportional limit (lb)
L = distance of specimen supports (in.)
A = cross-section of the specimen (in.^{2})
D = deformation at proportional limit (in.)

c. *Strength in axial compression* from the relationship:

$$C = \frac{P}{A}$$

where:

C = ultimate stress in axial compression (psi)
P = ultimate load (lb)
A = cross-section of the specimen (in.^{2})

This equation is usually applied to express the strength of wood in axial compression. Strength in transverse compression is determined as stress at proportional limit, where A = loaded surface, and strength in axial shear, where A = sheared surface.

Tests of static bending give the following properties:

a. *Stress at proportional limit in static bending* from the relationship:

$$S' = \frac{1.5\ P'\ell}{bd^2}$$

where:

S' = stress at proportional limit (psi)
P' = load at proportional limit (lb)
ℓ = length between beam supports (in.)
b = width of beam (in.)
d = length of beam (in.)

b. *Modulus of rupture (MOR) from the same relationship*, with P = ultimate load instead of P'. This is an approximate stress due to the assumption that linear behavior is sustained to level of failure.

c. *Modulus of elasticity (MOE) in static bending* from the relationship:

$$MOE = \frac{P' \ \ell^3}{4 \ Dbd^3}$$

where:

MOE = modulus of elasticity (psi)
D = deflection of neutral plane at proportional limit measure at half span (in.)

The other parameters are as previously defined.

Toughness is determined by tests intended to fracture the specimen with one stroke of a hammer acting in the form of a pendulum. The test is carried out in different ways. According to the American method, toughness is measured from the change of the initial angle to the final angle under which the pendulum is released, the change being due to a fracture of the specimen. Initial angles are set at 30, 45, or 60 degrees, and the position of the hammer, which is placed at the end of the pendulum, may change according to wood species. Indicative values of toughness, with this method, are calculated from the initial and final angles of the pendulum from tables, or from the relationship:

$$T = W\ell \ (\cos A_2 - \cos A_1)$$

where:

T = toughness, work per specimen (in.-lb)
W = weight of the hammer (lb)
ℓ = distance between the axis supporting the specimen and the center of the hammer (in.)
A_1 = initial angle (degrees)
A_2 = final angle, after fracture of the specimen (degrees)

5 Wood Durability Risk Factors In Service

Wood is valued for both strength and durability as a structural material in construction, and in general it can perform very well in a properly designed and maintained structure. However, wood is subject to deterioration through both environmental mechanisms and attack by living organisms. Damage severity can range from minor discolorations caused by sunlight to serious loss of cross-section or structural properties due to insect attack or fungi. Sometimes both routine and special precautions must be taken when wood is used in adverse environments.

5.1 Overview of Wood Deterioration Factors

Deterioration may be considered a general process that adversely alters wood's material properties. However, in order for the inspector to accurately assess the condition of a wood structure, he or she must understand specific causes, mechanisms, and contributing factors, which may greatly differ depending on the mode of attack. This knowledge will also help the inspector anticipate the rate of deterioration under the prevailing conditions and, if appropriate, prescribe treatments or repairs.

As noted, wood deterioration may be driven by physical environmental factors or attack by living organisms (i.e., biogenic deterioration). It can also be caused by a combination of these two basic modes., as well as the rate at which these processes occur under the prevailing conditions.

The structural performance and durability of each grade of wood used in construction is related to several key environmental factors: aging, effects of sustained temperature extremes, presence of chemicals, organisms, high humidity, and others. Field and laboratory testing to identify the grades of wood and to determine their mechanical properties may be used to establish actual structural properties.

Wood is subject to attack by various destructive agents. In general, wood that remains dry is relatively immune to attack from many of the destructive agents. However, although the color of the wood may slightly change from exposure to air and sunlight, and erosion may occur at a very slow rate from the slow breakdown of surface elements which are then washed away by rain.

Decay is one of the principal hazards faced by wood. It results from the action of certain types of fungi, which use the wood substance as a food source. Wood-destroying fungi require favorable conditions of moisture, temperature, and access to air. A number of insects and borers attack wood and destroy it; termites probably are the most destructive, especially in the southern United States. The chemicals commonly used to preserve wood from such attacks generally have little or no effect on material strength. The pressures and temperatures, used in the treating process, however, may reduce strength, and therefore are limited in standards for the treatment processes.

5.2 Effects of Aging

Age alone has no discernable effect on the properties of wood. However, load-carrying capacity decreases, at least for material relatively free of strength-reducing characteristics, when loading is at high levels and is continuous or even intermittent over long periods. Conversely, the load-carrying capacity is greater when loads are applied rapidly and for short duration.

In relatively dry and moderate temperature conditions where wood is protected from deteriorating influences such as decay, the mechanical properties of wood show little change with time. Test results for very old timbers suggest that significant losses in strength occur only after several centuries of normal aging conditions. The soundness of centuries-old wood in some standing trees also attests to the durability of wood.

5.3 Physical Causes of Wood Deterioration

The nonliving causes of wood deterioration fall under the general heading of exposure to energy, especially mechanical, thermal, and ultraviolet energy. Wood is also reactive to various chemicals and can be damaged by proximity to indirectly related chemical processes such as corrosion of metal fasteners. Table 10 and the next five subsections summarize the key effects that various nonliving stresses have on wood.

5.3.1 Mechanical Damage

Mechanical damage is the most significant physical agent in timber construction deterioration. It is caused by any number of factors — everything from wind-related erosion to repeated impacts that are part of daily facility operation. The effects of mechanical damage vary considerably, but even relatively minor effects may

lead to serious deterioration by opening the way for insect infestation, fungi, or other destructive factors.

5.3.2 Heat Damage

The strength of wood varies with its temperature, although the effects are small enough in the normal temperature range that they may generally be disregarded. Extremes of temperature are obviously reached when a wood member is subjected to fire, and a fire-exposed face of a wood member will, char or flame and become charred, the char having little strength. However, both wood and char are good insulators, and the wood just beyond the char wood interface will be subjected to temperatures well below those of the flame.

5.3.3 Ultraviolet Exposure

Some of the most visible wood deterioration results from exposure to the action of the ultraviolet portion of sunlight, which chemically degrades the wood surface (Figure 20). Ultraviolet degradation typically causes light woods to darken and dark woods to lighten, but this damage penetrates only a short depth below the surface (Feist 1983). The damaged wood is slightly weaker, but the shallow depth of the damage has little influence on overall strength except where continued removal of damaged wood eventually reduces the member dimensions.

5.3.4 Chemical Exposure

Chemicals may degrade wood, with the degree of degradation being reflected in varying degrees of loss in mechanical properties. Suitable service conditions for wood in contact with chemicals are (1) when the pH of the solution is between 2 and 11, (2) when the temperature is usually below 122 °F (50 °C), and (3) when there is no contact with oxidizing chemicals. The service life is shortened at extremes of the pH range, particularly at elevated temperatures. Wood products are sometimes treated with preservatives or fire-retarding salts, usually in water solution, to impart resistance to decay or fire. At levels of preservative treatments required for underground or ground-contact service, mechanical properties are essentially unchanged, except that work to maximum load, height of drop in impact bending, and toughness are reduced somewhat.

The effect of chemical solutions on mechanical properties depends on the specific type of chemical. Nonswelling liquids, such as petroleum oils and creosote, have no appreciable effect on properties. Mechanical properties are lowered in the presence of water, alcohol, or other wood-swelling organic liquids even though these liquids

do not chemically degrade the wood substance. The loss in properties depends largely on amount of swelling, and this loss is regained upon removal of the swelling liquid. The following generalizations summarize the effect of chemicals:

1. Some species are quite resistant to attack by dilute mineral and organic acids.
2. Oxidizing acids such as nitric acid degrade wood more than nonoxidizing acids. Oxidizing chemicals such as sodium and calcium hypochlorite swell and react with wood. They cause rapid loss of strength. Nitric acid also reacts rapidly with wood. The reaction rate and rate of strength loss are more rapid than would be predicted on the basis of pH and temperature.
3. Alkaline solutions are more destructive than acidic solutions. Alkaline chemicals such as sodium , calcium, and magnesium hydroxide will swell the wood structure, react with the hemicellulose and cellulose, and dissolve the lignin.
4. Hardwoods are more susceptible to attack by both acids and alkalies than are softwoods.

Wood can also be degraded by physical agents that generally act slowly, but can become quite serious in specific locations. Physical agents include mechanical abrasion or impact, ultraviolet light, and metal corrosion. Physical deterioration have similar effects to biotic attack, but the lack of visible signs of fungi or insects, in addition to the general appearance of the wood, can indicate to the inspector the nature of the damage. Physical agents can also damage preservative treatments, thereby exposing the wood to biotic attack.

5.3.5 Incidental Effects of Corrosion

Wood degradation resulting from metal corrosion, typically related to metal fasteners, is frequently overlooked as a cause of deterioration. This type of degradation can be significant in some situations, particularly in marine environments where saltwater galvanic cells form and accelerate degradation (LaQue 1975). In addition to the deterioration caused by corrosion, the high moisture conditions associated with this damage can initially favor the development of fungal decay. However, as corrosion progresses, the toxicity of the metal ions and the low pH in the wood eventually eliminate fungi from the affected zone (although decay may continue at some distance away from the fastener). The effect of corrosion-induced wood deterioration can be limited by using galvanized or noniron fasteners.

Table 10. Relative effects of various energy forms on wood.

Form of energy	Indoor		Outdoor	
	Result	Degree of effect	Result	Degree of effect
Mechanical	Wear and tear	Slight	Wear and tear	Slight
			Wind erosion	Slight
			Surface roughening	Severe
			Defiberization	Severe
Thermal				
Intense	Fire	Severe	Fire	Severe
Slight	Darkening of color	Slight	Darkening of color	Slight
Light				
Visible and UV	Color change	Slight	Large color changes	Severe
			Chemical degradation	Severe
Chemical	Staining	Slight	Surface roughening	Severe
	Discoloration	Slight	Defiberization	Severe
	Color changes	Slight	Selective leaching	Severe
			Color changes	Severe
			Strength loss	Severe

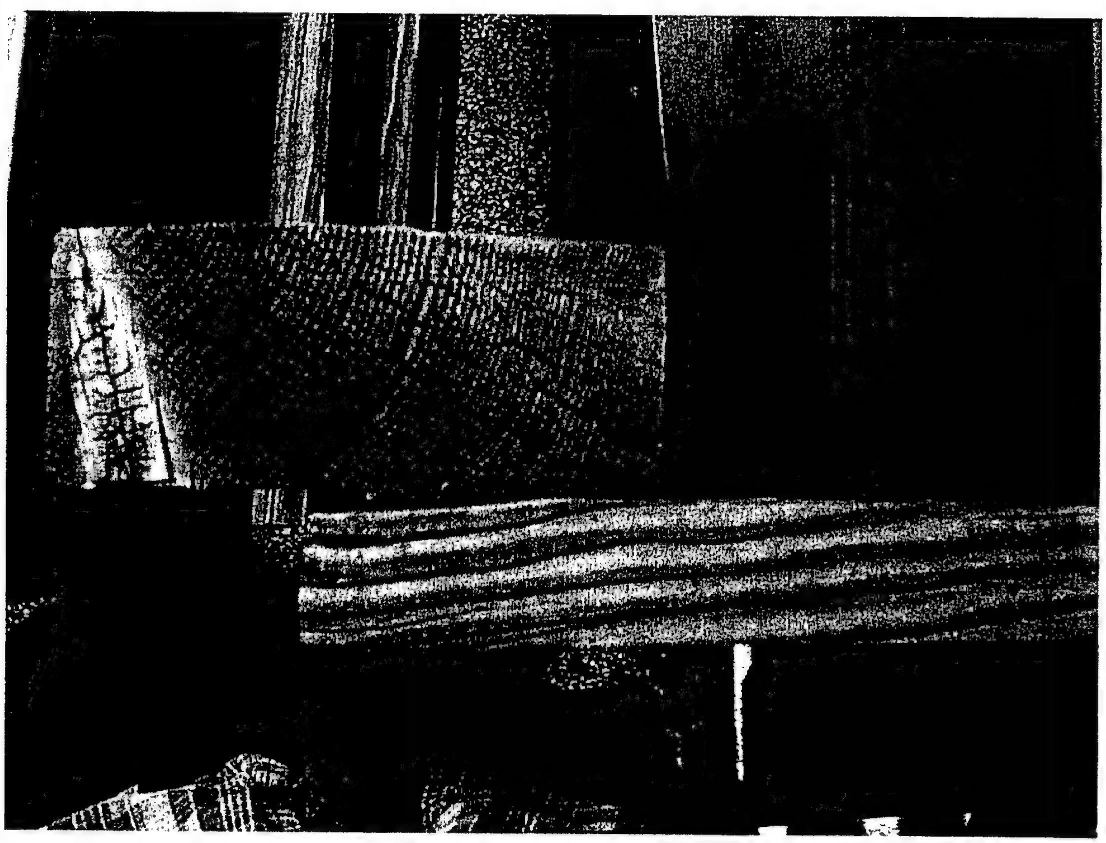


Figure 20. Ultraviolet light degradation.

5.4 Biogenic Causes of Wood Deterioration

A number of living organisms, including insects, bacteria, and fungi, can use wood as part of their life cycle. Some of these organisms use wood for food and others alter it to use as shelter. Both macroscopic and microscopic life forms have the ability to change and deteriorate wood.

5.4.1 Enabling Factors

5.4.1.1 'Life-Support' Requirements for Wood-Damaging Organisms

All organisms require certain basic conditions for survival, including water, food, oxygen, and a suitable temperature. Different organisms depend on each factor to differing extents, but all of these factors must be in place for an organism to alter or consume a mass of wood. Elimination of any essential component from the wood environment will protect the wood from biogenic deterioration.

Oxygen is difficult to eliminate from wood used above ground, but airtight wraps have been successfully used to protect underwater pilings from borers. Temperature is also difficult to control, but some heat treatments can effectively provide temporary sterilization (i.e., destruction of microorganisms, spores, etc.).

Moisture is the 'life-support' factor most readily controlled by structural design — for example, the use of effective drainage details, quality membranes, and appropriate coatings and sealants. In areas where moisture cannot be mostly excluded, however, chemical treatment may be needed to make the wood noxious or toxic to troublesome organisms.

5.4.1.2 Moisture Content Issues

Moisture control is a fundamental concern in the design of durable wood structures not only because water is a requirement of wood-damaging organisms, but also because the actual amount of water in the wood is a major factor in determining which types of organisms are present and how quickly they degrade the wood. Generally, moisture content below the fiber saturation point (i.e., about 30 percent) will not decay. However, many insects and some specialized fungi can attack wood at much lower moisture levels.

In addition to supporting the metabolic processes of insects and microorganisms, moisture content plays another significant role in wood deterioration. When water enters wood, the microstructure swells until the fiber saturation point is reached.

Continuous exposure to water or repeated cycles of drying and wetting can leach protective chemicals out of the wood. This problem may affect both wood preservatives added during manufacture as well as naturally occurring chemicals in the wood that provide decay resistance.

5.4.2 Varieties of Wood-Damaging Organisms

5.4.2.1 Insects

Insects are among the most common organisms on earth, and a number of species use wood for shelter or food. Of the 26 insect orders, 6 cause wood damage. Termites, beetles, bees, wasps, and ants are the primary agents of most insect-related deterioration. In addition to removing portions of the wood structure, insects may also carry stain and decay fungi that further deteriorate wood.

5.4.2.1.1 Termites. More than 2000 species of termites are found in areas where the average annual temperature is 50 °F or higher. Termites are by far the most economically significant wood-destroying insects. In some cases, termites extend their range into cooler climates by living in heated structures. They attack most wood species, but the heartwood of a few species, such as southern cypress, exhibits some resistance to attack.

Depending on their type, termites vary in moisture requirements from very high to very low. The dampwood termites of the western United States require damp wood for successful colonization. Subterranean termites also have a high moisture requirement, but as long as they have access to a source of water, they can attack very dry wood. The range of moisture tolerance by drywood termites varies greatly depending on the species. Subterranean termites feed principally upon earlywood, thereby forming irregular tunnels confined within the annual rings.

Dampwood termites are common to the Pacific Northwest although one group is found in the more arid southwest. The most common dampwood species is found along the Pacific coast from northern California to British Columbia.

Drywood termites differ from subterranean and dampwood termites in their ability to attack wood that is extremely dry, i.e., 5 – 6 percent moisture content. As a result, drywood termites attack wood not in ground contact and away from visible moisture sources. Wood damaged by these insects has large, smooth tunnels that are free of excrement and debris.

5.4.2.1.2 Beetles and Ants. Beetles comprise the largest order of insects which includes nine families that cause substantial damage to wood. Some insects require high moisture content in wood to initiate attack. The large wood borers such as beetles begin attacks on dying trees, green logs, or wet wood. Different species of beetles attack hardwoods and softwoods. In the United States, beetle infestations of wood structures are similarly associated with higher moisture content. In the humid southern States, beetles are becoming more prevalent. They benefit nutritionally from fungally decayed wood, which indicates that they favor wood whose ambient moisture content rises above 20 percent.

Carpenter nest in naturally soft wood or wood softened by fungal decay. The wood also must be moist or located in a high humidity. To form nests, ants excavate large cavities that have clean interior surfaces and cross several annual rings. Ants do not eat wood, so they are not deterred by distasteful chemicals such as those naturally present in redwood and other softwoods.

5.4.2.2 Bacteria

Bacteria are generally considered to have little effect on wood strength, but infestation can degrade the material and make it more susceptible to other kinds of damage. Bacteria are mostly single-celled organisms, passively dispersed within the environment. They grow upon a food substrate. Bacteria require free water to grow, and they are common in saturated, water-soaked, or moist wood. The initial consequence of bacterial infestation of wood is a notable increase in permeability (i.e., by a factor of 7 – 10 times), a slight decrease in toughness, although no loss in specific gravity is observed. Also, discolorations, softening of surface layers, and excessive shrinkage have been attributed to bacteria. Long-term bacterial action may cause significant modification of strength properties. In one example, the authors have observed significant reduction in bending strength, stiffness, and specific gravity in red pine piles used in a river environment, evidently due primarily to bacterial action; lumber cut from this material could not be considered suitable for structural use according to published allowable design stresses for the species.

5.4.2.3 Decay Fungi

The use of pressure-treated wood has significantly extended the life of timber, but decay is still the primary cause of deterioration in most structures. The fruiting bodies that grow on wet or damp wood are commonly blamed for wood rot. However, it is the vegetative portion of these fungi, growing within the wood, that causes decay or rot. Wood decay fungi are mainly grouped into three categories; white rot, which tends to bleach the affected wood; brown rot, which produce a

brown, crumbling type of decay; and soft rot, which causes a progressive softening of the wood surfaces.

A film of moisture has to be present on the surface of wood cell walls for typical decay fungi to grow. It is generally assumed that wood with a moisture content below 20 percent is safe from decay and that wood with a moisture content above 30 percent will be susceptible to decay unless otherwise protected. The upper limit of wood moisture content that permits decay is dependent upon the specific gravity and relative volume of void space within the wood.

The soil constitutes a major potential source of moisture, and the decay hazard is always great for untreated wood in contact with the ground. As a result, building codes and standards specify minimum distances between untreated wood products and ground level. Hardwoods and softwoods that are in contact with soil are attacked by brown and white rot fungi. Hardwood species are more likely to be attacked by soft rot fungi. Brown rot fungi predominate in softwood used above ground. Therefore, brown rot is the predominant type of decay in above-ground construction. Brown rot fungi cause a more rapid loss of mechanical properties per unit of weight loss due to decay than do white rot fungi.

Seepage can affect the potentials for decay at the ends of wood members. Water is absorbed by wood more rapidly and to a greater depth through transverse surfaces than it is through either the radial or tangential surfaces, hence contributing toward decay.

With the presence of brown rot in some woods, the modulus of rupture and work to maximum load in static bending are often drastically reduced even though little or no weight loss is observed. In practical terms, a crumbling type of decay is visible evidence that the mechanical properties of the affected wood have been seriously reduced. At advanced stages, brown rotted wood is brittle and has numerous cross checks, similar in appearance to the face of a heavily charred timber (Figure 21). The brown rots primarily attack the wood cell wall causing weight loss of nearly 70 percent. The brown rot fungi cause substantial strength loss at the very early stages of decay. At this point, the wood appears sound and the fungus may have removed only 1 to 5 percent of the wood weight, but some strength properties may be reduced by as much as 60 percent (Wilcox 1978). Brown rot fungi may reduce the mechanical properties of wood in excess of 10 percent before a measurable weight loss is observed and before there are visible signs of decay. When weight loss reaches 5 – 10 percent, the mechanical properties are reduced from 20 – 80 percent. Toughness, impact bending, and work to maximum load in bending are reduced most, shear and hardness the least; other properties show an intermediate effect.

Figure 21. Wood infected with brown rot fungi.

5.4.2.4 Stain Fungi

Stain fungi produce bluish-black to steel-gray or brownish discolorations in the sapwood of freshly cut trees and lumber, and in unprotected sapwood of rewetted, previously dried wood. The dark-colored fungi initially colonize the ray tissues of softwoods. Stain fungi attack sapwood soon after it is cut and may continue to grow in softwoods until the wood moisture content drops below approximately 25 percent. A fully developed stain in naturally infected sapwood of southern pine may reduce the specific gravity by 1 – 2 percent, strength in compression parallel to the grain, the modulus of rupture from 1 – 5 percent, and toughness by 15–30 percent.

Fungus-stained wood may have incipient decay. Kiln drying kills fungi in wood, but the permeability of stained wood remains and, when exposed to rain, it will absorb more water than will unstained wood. This can promote decay. In the U.S. Gulf States, decay has been observed to develop soon after construction in southern pine siding suspected as being stained or having incipient decay at the time of installation. In contrast, siding produced from kiln-dried wood had essentially no decay after 5 – 10 years of service on comparable buildings.

Under favorable conditions, some stain fungi may continue to degrade wood, decreasing toughness and increasing permeability; consequently, stained wood is gen-

erally rejected during grading for structural uses. Stain fungi use the contents of the wood cell for food, but do not degrade the cell wall. Although they do not adversely affect strength, their presence can indicate conditions favorable for the growth of decay-causing fungi.

5.4.3 Deterioration Impacts and Protective Actions

5.4.3.1 Effects of Decay

Decay fungi can cause substantial loss in mechanical properties. This is quite evident when decay is highly advanced, such as when the wood has become friable and light in weight. For intermediate stages of decay, however, there is no way to estimate accurately the loss in strength and related properties. One measure of the progress of decay is the amount of weight loss due to fungal attack. Insects can largely destroy a piece of wood without much external evidence of damage. Marine organisms likewise may destroy much of the wood in members which have been exposed to salt or brackish water, especially in tropical waters. Structures that are suspect require careful examination by sounding, boring, x-ray, or other examination to determine the impact of wood damage on load-carrying capacity.

Early stages of decay are virtually impossible to detect, but some fungi can nevertheless reduce the mechanical properties in excess of 10 percent before any weight loss or visible signs of decay are observed. When weight loss reaches 5 – 10 percent, the mechanical properties may be reduced from 20 percent to as high as 80 percent. Toughness, impact bending, and work to maximum load in bending are reduced most, shear and hardness the least, while other properties show an intermediate effect.

A flowchart indicating the basic decay detection process is presented in Figure 22.

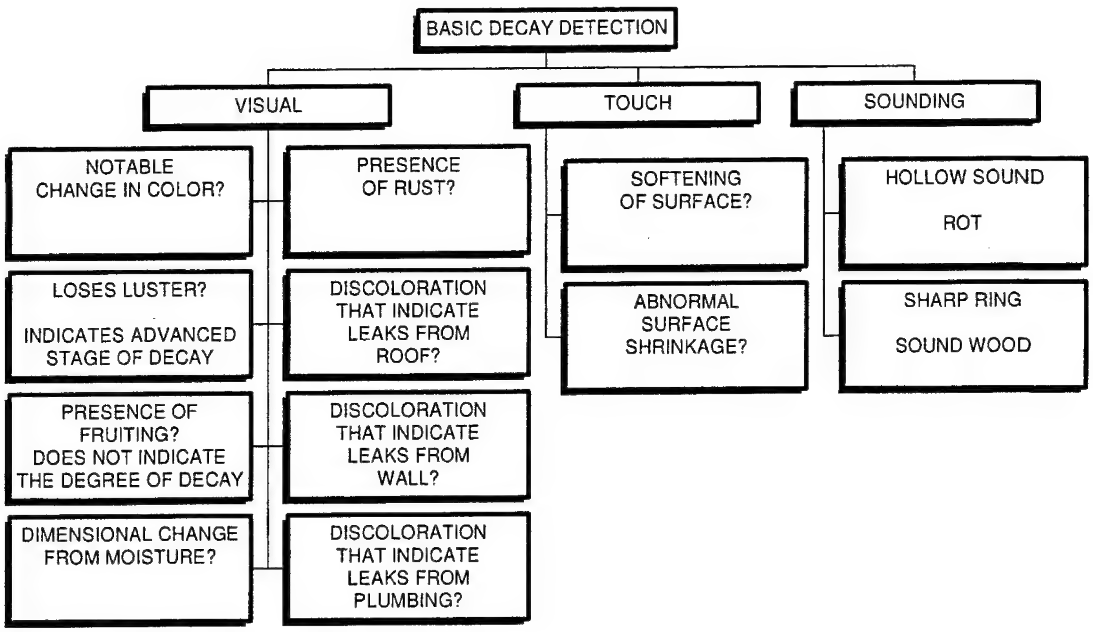


Figure 22. Basic decay detection process.

Structural members infected with decay fungi experience progressive strength loss as the fungi develop and degrade the wood structure. The degree of strength reduction depends on the area of the decay and the stage of development. At the advanced or intermediate stages, wood deterioration progresses to the point where no strength remains in the infected areas. At this stage, suitable detection methods can be used by the inspector to accurately define the affected areas with some degree of certainty. At the early stages of development, however, detection is much more difficult and the effect of strength loss varies among various types of fungi.

Some investigations on assessing strength loss have indicated that strength loss associated with some brown rot fungi can be as high as 50 – 70 percent when the weight is reduced by only 3 percent or less (Hartley 1958; Kennedy 1958). In light of the large strength losses associated with early brown rot development, it is recommended that no strength value be assigned to wood showing evidence of decay in any stage of development. Although this approach may result in a conservative evaluation, it is the only safe approach for assessing strength given the large number of variables involved. Although numerous cores may be taken to define the decayed area, the possibility remains that the entire area of infection will not have been sampled. Furthermore, decay will continue to further reduce strength unless immediate maintenance actions are undertaken to inhibit its growth. Section 6.2 (Chapter 6) provides the inspector more detail on procedures and techniques for detecting decay.

5.4.3.2 Protective Measures Against Deterioration

Decay can be prevented from starting or progressing if wood is kept dry, i.e., below 20 percent moisture content. The use of decay-resistant species, pressure-treated members, or chemical applications may also be appropriate if structural and environmental compliance requirements can be met. Furthermore, various design details can be very useful in eliminating problem areas where, for example, excessive moisture can accumulate or be absorbed into the grain.

5.4.3.2.1 Wood Preservatives. Treatment of wood with preservative chemicals contributes to resistance against bacteria, fungi, and insects. The degree of protection rendered depends upon the process, level of treatment, and the chemicals used. Treatment processes may provide either superficial or in-depth protection to wood. Water-repellent preservatives are applied either by dipping precut lumber in treatment solutions or by application at the construction site. However, such treatments do not provide protection for wood used in contact with the ground or in other uses with an equally severe decay hazard.

5.4.3.2.2 Structural and Finishing Design. Design details that protect above-ground wood from decay and insects work either by protecting wood from exposure to water or by using decay-resistant woods where high moisture contents are anticipated. Because of the prevalence of brown rot type of decay in above-ground construction, special design attention should be given to eliminating potential water entrapment and end-grain absorption of water at inter-surface contacts. In architecture, roof overhangs should be designed to protect critical areas from precipitation, and buildings should be oriented to provide maximum protection to exposed wood members. Exposed timbers should be treated with preservative.

6 Comparing Current Condition With As-Built Condition

This chapter discusses techniques that consider the age of a structure and the version of the building code employed to engineer it in order to estimate reductions in margins of safety compared to current building codes and due to material degradation. Information is provided to help inspectors determine the margin of safety of the structure compared with its original design and compared with current code requirements. A rating system is developed based on existing codes to evaluate and assess structures that were designed and constructed using old codes.

6.1 Inspection

6.1.1 Introduction

Thorough inspection of a structure is essential before repair, modification, or upgrading. The inspection provides knowledge of the structure and its components, the loadings to which it is or has been subjected, the quality of the materials involved and their condition, and the effectiveness of the fastenings. These factors must be known in order to evaluate the ability of the structure to perform its intended function, to establish the procedures necessary to restore its original purpose, or to prepare it for a new function.

Establishing the cause of damage or structural deficiency is significant in developing methods of repair. Sound inspection methods can be vital to the establishment of reasons for structural disability. Inspection may be carried out for several purposes and the inspection procedures are likely to differ depending upon the purpose. Various structural deficiencies and in-place repairs that can be encountered during a visual inspection are shown in Figures 23 – 29.

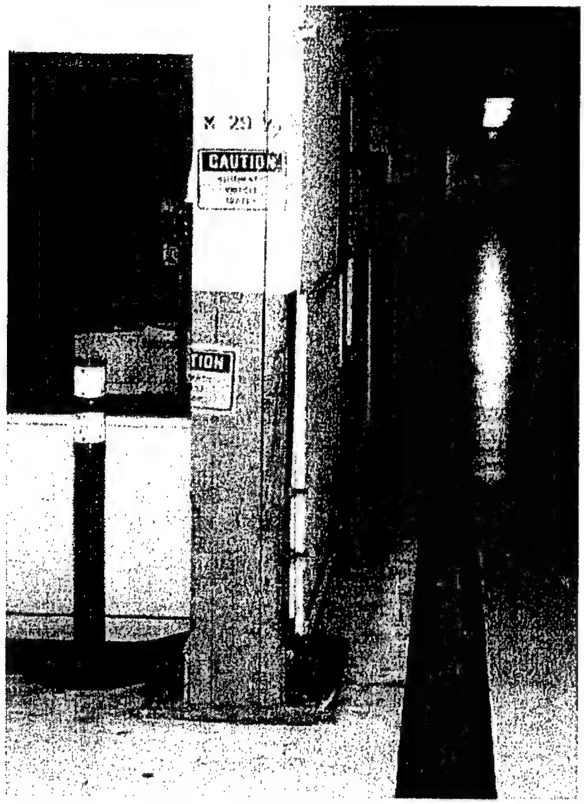


Figure 23. Column damaged by passing objects.

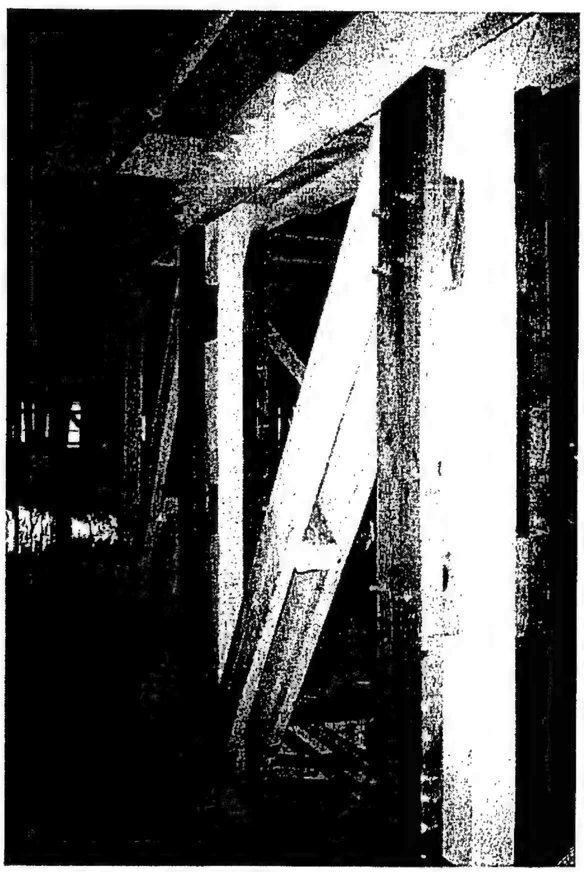


Figure 24. Typical type of existing repair.

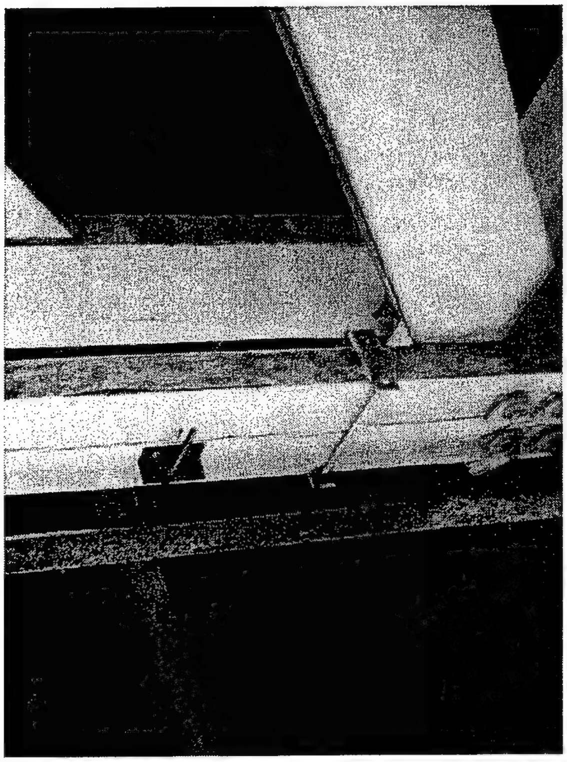


Figure 25. Another typical type of existing repair.

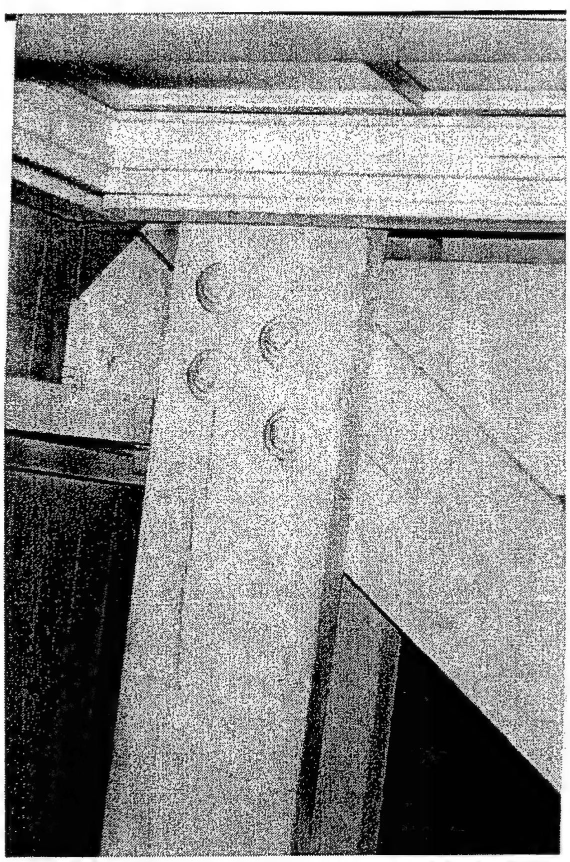


Figure 26. End split in diagonal member.

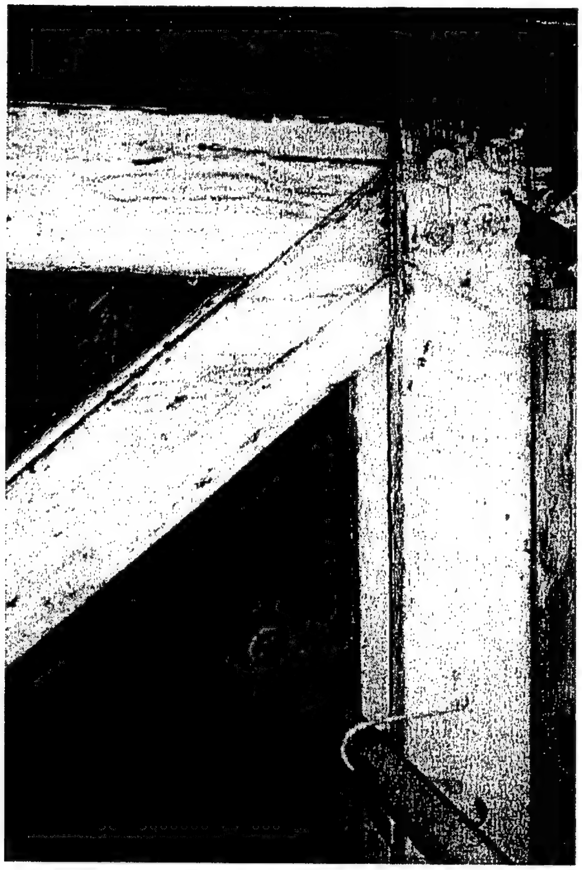


Figure 27. Major damage due to decay.

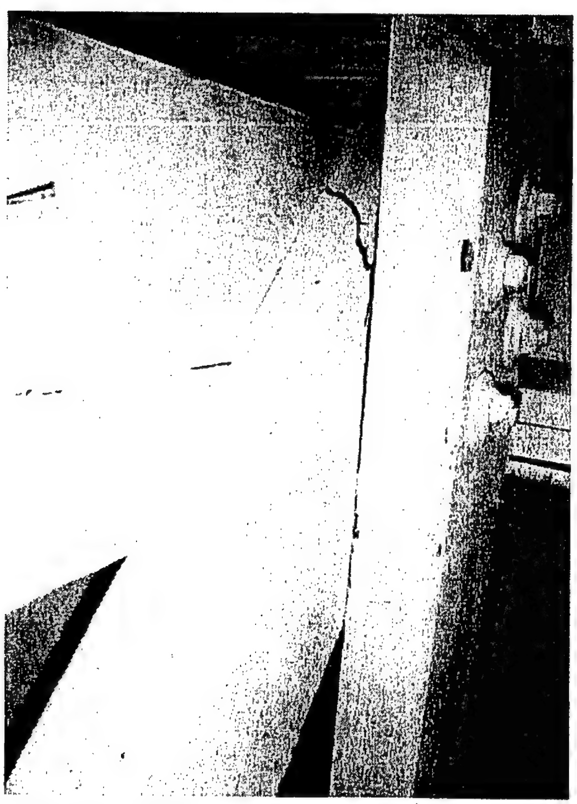


Figure 28. Fracture in diagonal member.

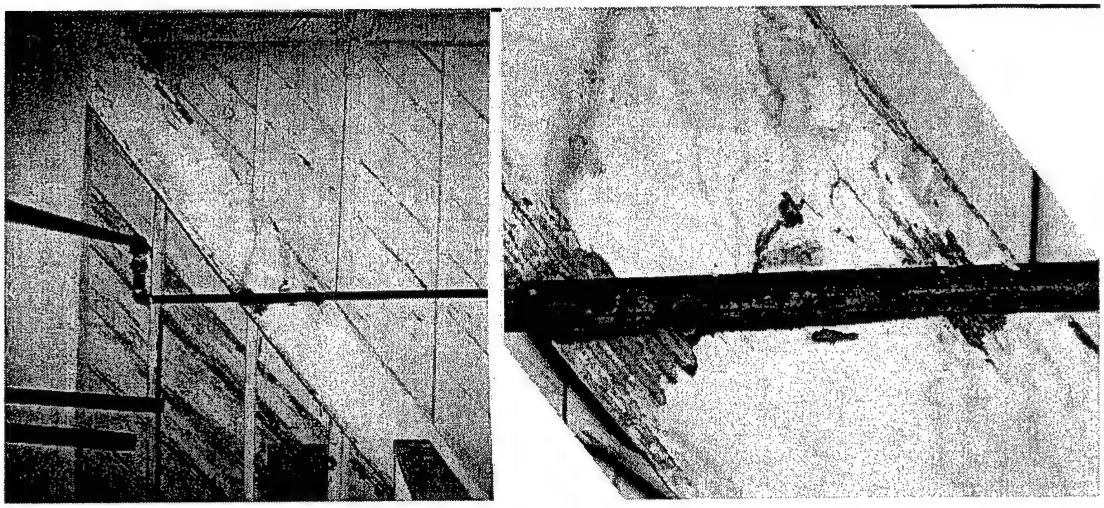


Figure 29. Tension failure in diagonal member.

6.1.2 Preventive Maintenance

A structure should be examined for obvious problems such as fractured members, obvious distress short of fracture, and loadings not provided for in design. Dimensional changes caused by moisture changes, combined with vibration and other factors, can cause a general loosening of bolted connections. This phenomenon can become a serious problem if significant reduction of bearing area or disengagement of connectors occurs. Bolts should be tightened when members approach moisture equilibrium at the end of 4 or 5 months of operating conditions, and at approximately 5-year intervals thereafter.

All members should be inspected for decay or insect infestation, with special attention to areas where there is evidence of high moisture content. Checks, splits, and delamination should be examined to determine whether the openings are exceed the limits imposed by the lumber grade.

6.1.3 Evaluation of Revised Loadings

Original architectural and structural documents should be located and considered in the evaluation process. Requirements of the code under which the structure was designed and built should also be considered. In addition to providing the requirements for the original structure, the historic building code text will provide information on the extent of upgrading required. Special attention must be given to current or planned loadings and to their points of application, and these must be compared with the design assumptions. Member sizes and grades must be established to determine their suitability under any new conditions of use and loading.

6.1.4 Evaluation of Distressed Structure

The main objective of the inspection is to determine whether structural distresses pose an immediate threat to life or property. This is necessarily an engineering judgment and the determination cannot be made on the basis of general guidelines. Several issues must be addressed, and the appropriate decisions must be made with respect to the necessity of evacuation the structure, reoccupation of the structure upon completion of the shoring, completion of repairs without disruption of normal use, and the magnitude of the distress.

Some of the potential causes of distress include overloading, whether due to snow, ponding, or unplanned addition of equipment; loads applied to the structure at points not planned for; splits, delamination, or other openings; fractures, distortions, or misalignment of members; failure or distress in connections; and deterioration of materials.

6.2 Methods of Detecting Deterioration

Deterioration in timber structures falls into two broad categories: exterior deterioration and interior deterioration. In both cases, specific methods or tools are appropriate for certain types of damage, and their usefulness varies depending on the type of the structure. The methods or tools are often dictated by economy, experience, and the types of problems encountered. Figure 30 shows a flowchart for material testing for decay.

6.2.1 Methods for Detecting Exterior Deterioration

Exterior deterioration is the easiest to detect because it is often visible to the inspector. The ease of detection depends on the severity of damage and the method of inspection. These methods include visual inspection, probing, and the pick test. When areas of exterior deterioration are located by these methods, further investigation by other methods is required in order to confirm and define the extent of damage.

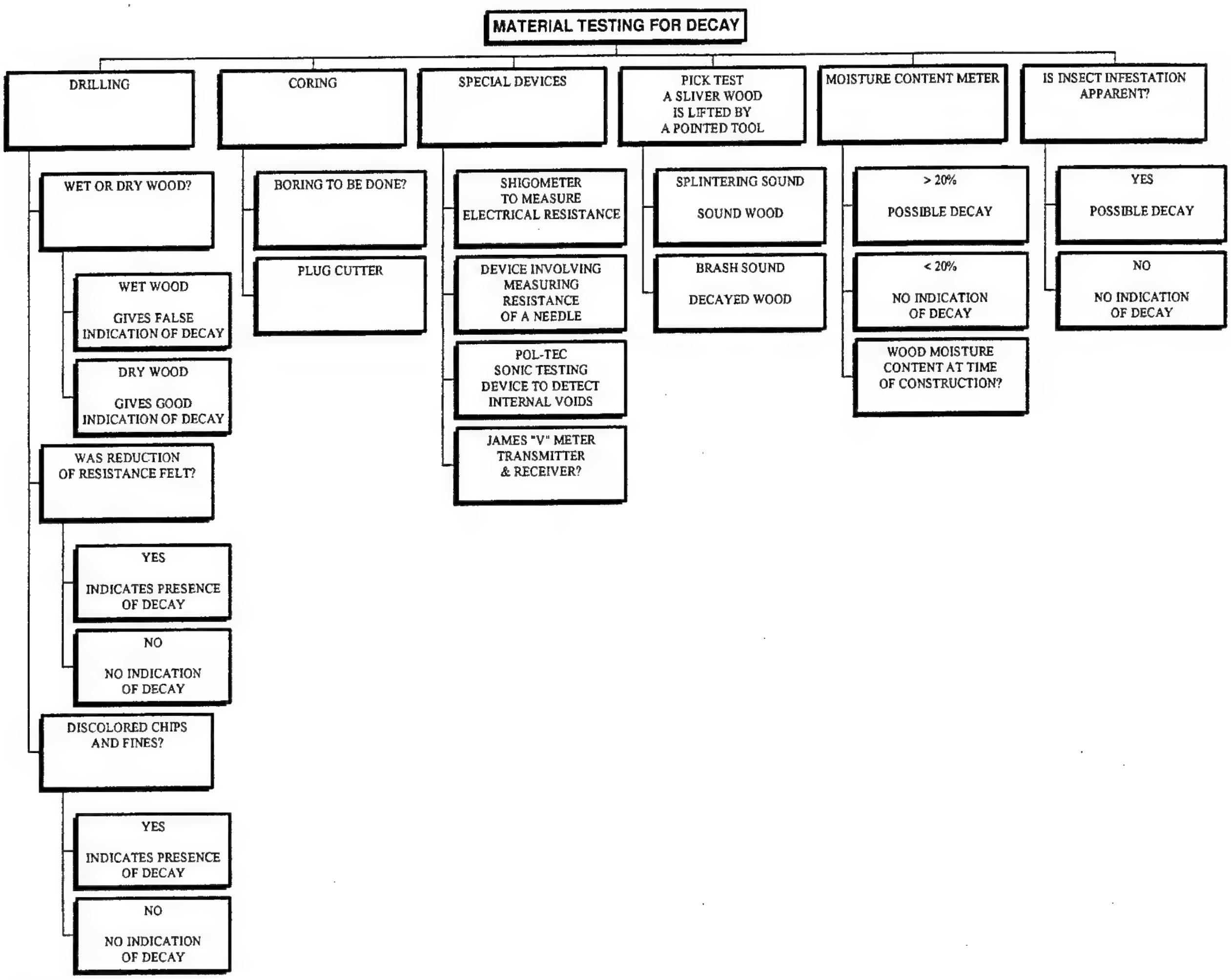


Figure 30. Material testing procedures for decay.

6.2.1.1 Visual Inspection

The color of wood may or may not be an indication of decay or deterioration. Wood at the advanced stages of decay loses luster and may show notable changes in color. However, at early stages, the wood may appear unaffected even though it may have lost substantial percentages of its strength, particularly in shock resistance.

The presence of fruiting bodies (Figure 31) indicates that a decay fungus is present in the member. Some fungi produce fruiting bodies after little or moderate decay while others do not produce fruiting bodies until after extensive decay has occurred. Fruiting bodies provide positive indication of fungal attack, but however they do not indicate the extent of decay.

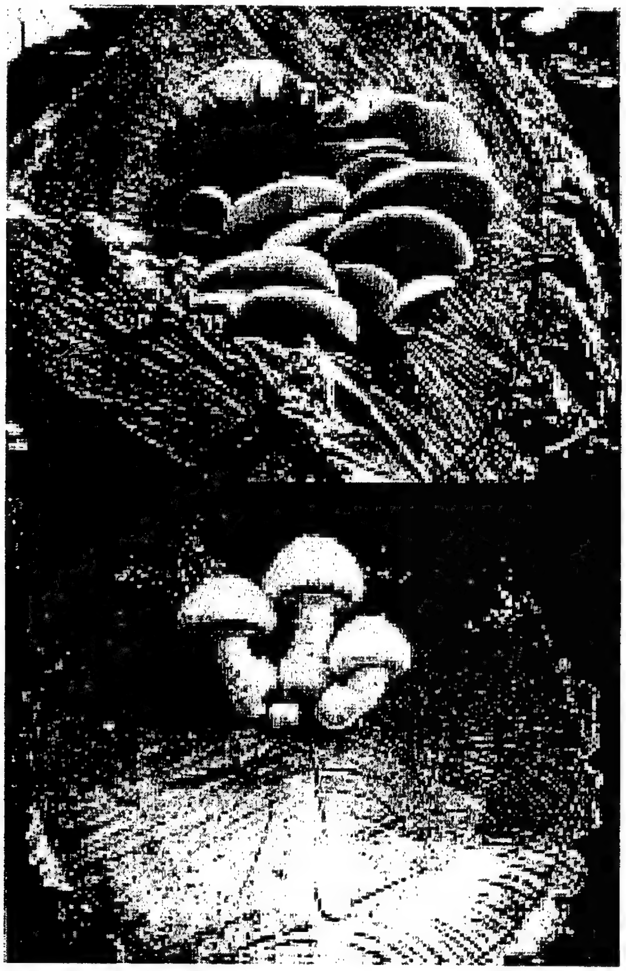


Figure 31. Examples of decay fungus fruiting bodies.

Another visible clue to the presence of decay is a localized depression or sunken faces over decay pockets which extend close to the surface of the member. Termites, beetles, and carpenter ants are associated with decayed wood, and infestations by these insects may be evidence of decay.

A number of conditions provide visual evidence of decay, and areas exhibiting these conditions should be inspected carefully. Evidence of water, such as watermarks, indicate areas that may have been at a high moisture content, and thus should be investigated. Rust stains on wood surfaces also indicate possible excessive wetting. Appreciable growth of moss or other vegetation on wood surfaces or in checks or cracks is evidence of potentially hazardous wetting. Special attention should be given to wood adjacent to water-trapping areas, such as joints where end-grain surfaces are found, and at interfaces between members. Figure 32 provides an overview of the inspection process and Table 11 presents a checklist of the inspection equipment needed.

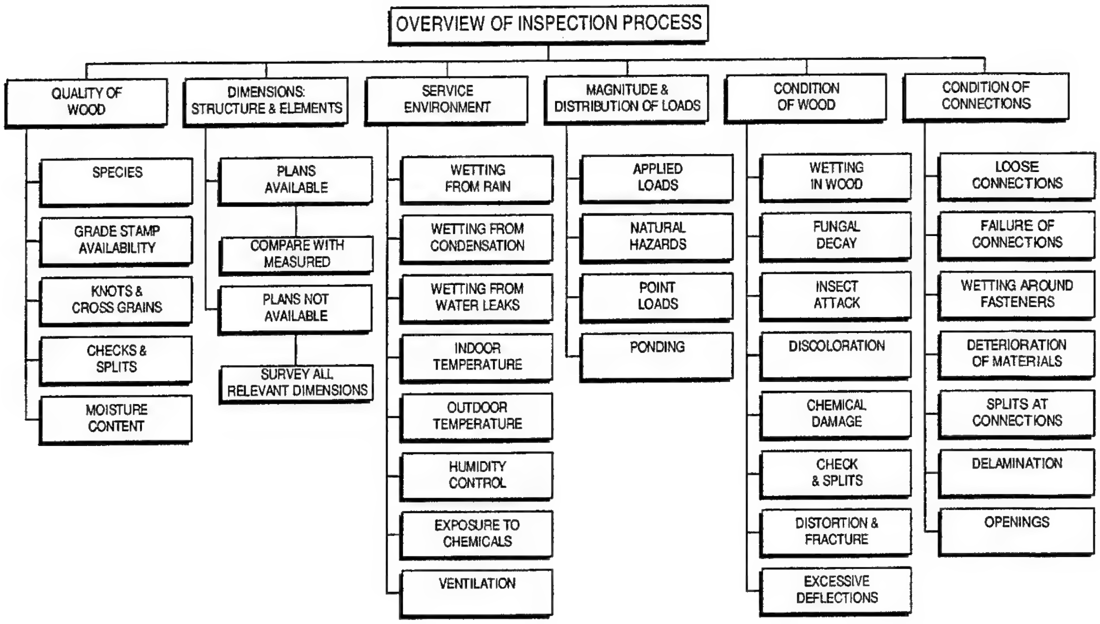


Figure 32. Overview of inspection process.

Table 11. Checklist of inspection equipment.

Equipment	Purpose
Light sources	for illuminate dark areas, shadowed heights, and inaccessible locations
Ladder, forklift	to give easy accessibility for various structural members at high locations
Rulers, measuring tapes	to measure the magnitude of defects widths and lengths as well as to check the amount of deflection; thickness gage to measure the depth of checks or delamination
Probes, awls, knives	to detect decay that extends close to the surface
Hammers	for sounding to indicate the presence of interior deterioration
Drilling equipment	to determine the presence of internal deterioration
Treated wood plugs	to close holes bored for inspection purposes
Moisture meter	to determine the moisture content
Camera	for recording the condition of the member under inspection
Hand level	for leveling
Magnifier (10x)	to examine small details of deterioration, wood infestation, etc.

6.2.1.2 Probing

Probing with a pointed tool such as an awl or knife locates decay near the wood surface by revealing excessive softness or a lack of resistance to probe penetration. Probing is a simple inspection method, but experience is required to interpret the

results. A difficulty arises from differentiating between decay and sound wood that is essentially water-softened and therefore somewhat softer than dry wood.

6.2.1.3 Pick Test

The pick test is one of the simplest and most widely used methods for detecting surface decay. A pointed pick, awl, or screwdriver is driven a short distance into the wood and used to pry out a sliver (Figure 33). The wood break is examined to determine if the break is brash (decayed) or splintered (sound). Sound wood has a fibrous structure and form splinters when broken across the grain. Decayed wood breaks abruptly across the grain or crumbles into small pieces. Several studies indicate that the pick test is reasonably reliable for detecting surface decay. The only drawback to this method is the cosmetic blemishes that result from removing samples of the wood.

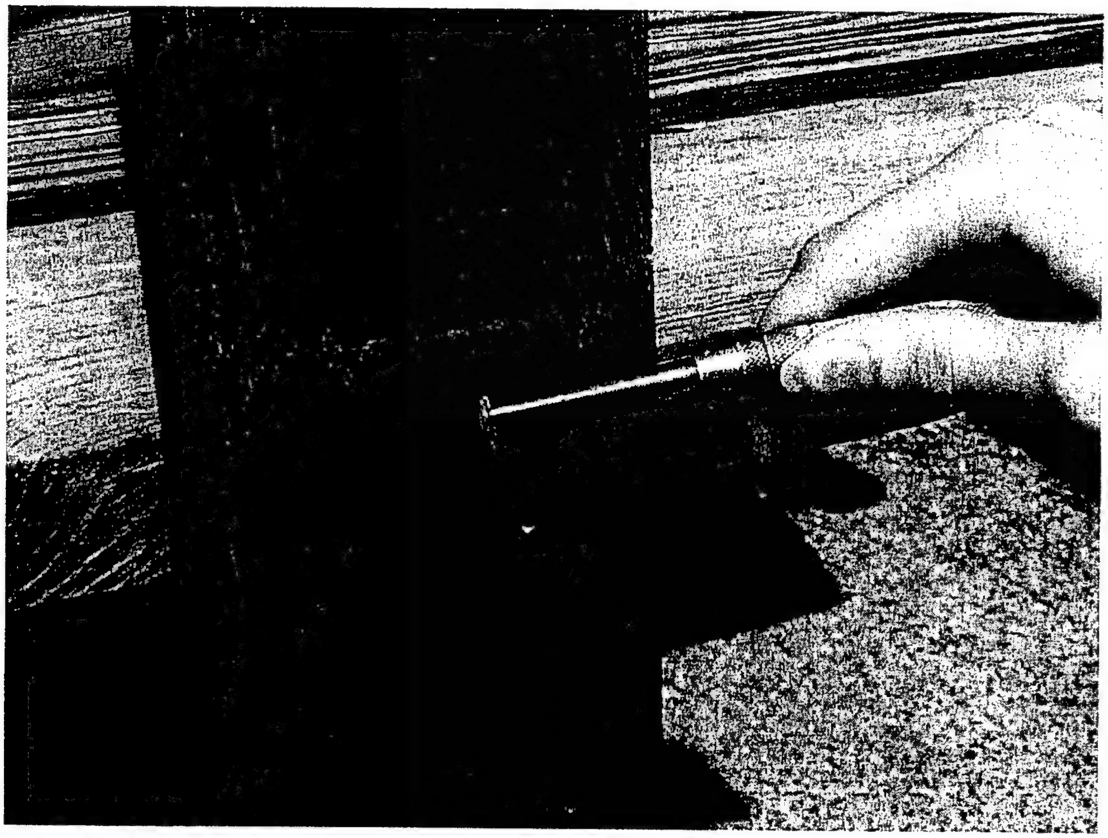


Figure 33. Pick test for detecting early wood decay.

6.2.2 Methods for Detecting Interior Deterioration

Unlike exterior deterioration, interior deterioration is difficult to locate because there may be no visible signs of its presence. Numerous methods have been developed to evaluate internal damage. These range in complexity from sounding the

surface with a simple hammer to sophisticated sonic or radiographic evaluation. In addition, such tools as moisture meters are used to help the inspector identify areas where conditions are suitable for development of internal decay.

6.2.2.1 Sounding

Sounding with a hammer is a simple, rapid, and effective method for detecting extensive internal decay. A sharp ring when a wood member is struck indicates sound wood, whereas a hollow sound or a dull thud may indicate rot. Although sounding is widely used, it is often difficult to interpret because factors other than decay can contribute to variations in sound quality. Furthermore, sounding provides only a partial indication of the extent of decay present and it does not detect wood at the incipient or intermediate stages of decay. Also, shakes and checks can affect the sound. Therefore, suspicious areas should be drilled or cored to confirm an initial indication of decay.

6.2.2.2 Moisture Content Meters

Resistance-type moisture meters (Figure 34) are very useful for determining whether wood contains insufficient moisture to support decay (i.e., less than about 20 percent). This unit uses two metal pins that are driven into the wood to measure electrical resistance, which is a function of moisture content. Pins are available in various lengths for determining moisture content at depths up to 3 in..

Although meter displays are calibrated to measure water content of about 7 – 65 percent, the accuracy of the readings decreases above 20 percent. It should be noted also that meter readings may be erroneous where members have been treated with waterborne salt-based chemicals.

Moisture contents higher than 30 percent indicate conditions suitable for decay development unless the wood in the immediate area is treated with preservatives and no breaks occur in the treatment process. If inspection is conducted after an unusually long period of dry weather, even lower moisture levels in the range of 20 to 25 percent can indicate potentially favorable conditions for damage.

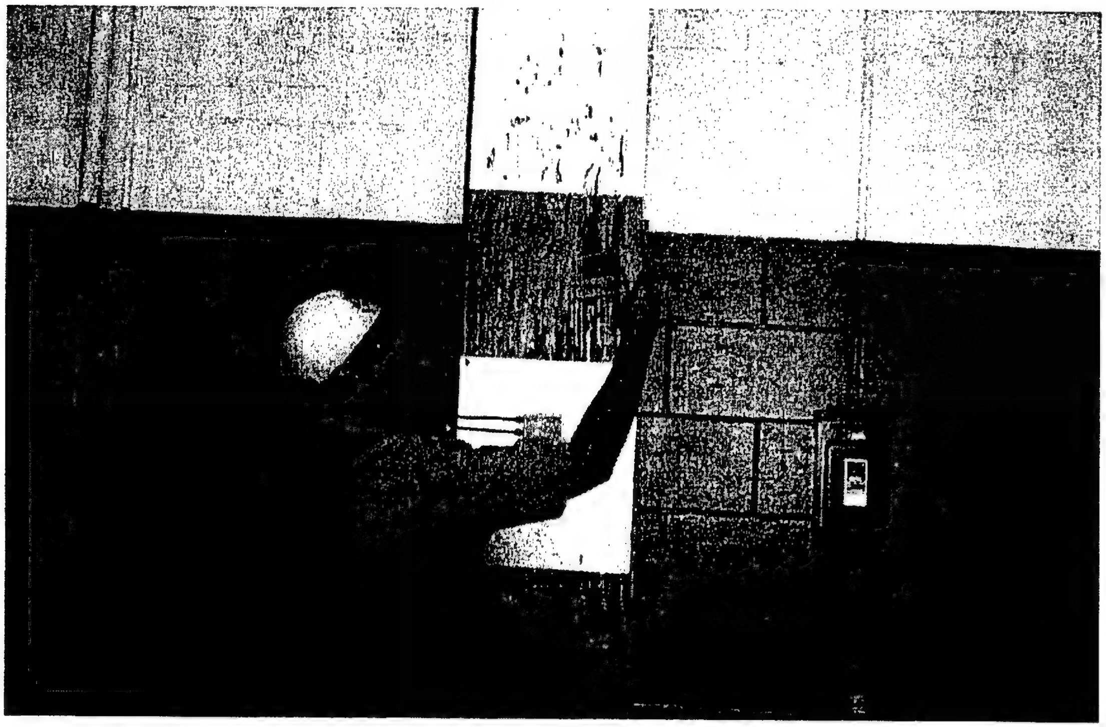


Figure 34. Using a moisture meter.

6.2.2.3 Drilling and Coring

Drilling and coring are the most common methods for detecting internal deterioration in wood structures. Both techniques are used to detect the presence of voids and to determine the thickness of the residual shell when voids are present.

Drilling, either with a brace and bit or with an electric drill, indicates rot by reduced resistance, which may be abrupt when voids are present. Wet wood may give a false indication of decay. Discolored chips and fines indicate decay. The presence of common wood defects such as knots, resin pockets, and abnormal grain should be anticipated while drilling and must not be confused with decay. Shell thickness may be determined by inserting a thin metal rod with a hook on the end into the hole and pulling the rod back until the hook catches on the edge of the rot pocket. This procedure works best in cedar, where transition from sound to rotted heartwood is abrupt, but can be misleading in nondurable heartwoods such as Douglas Fir and pine.

Coring with increment borers also provides information on the presence of decay pockets and other voids, and coring produces a solid wood core that can be carefully examined for evidence of decay (Figure 35). Drilling and coring are generally used to confirm suspected areas of decay identified by the use of moisture meters or other methods. When decay is detected, drilling and coring are also used to further define the extent and limits of the decay.

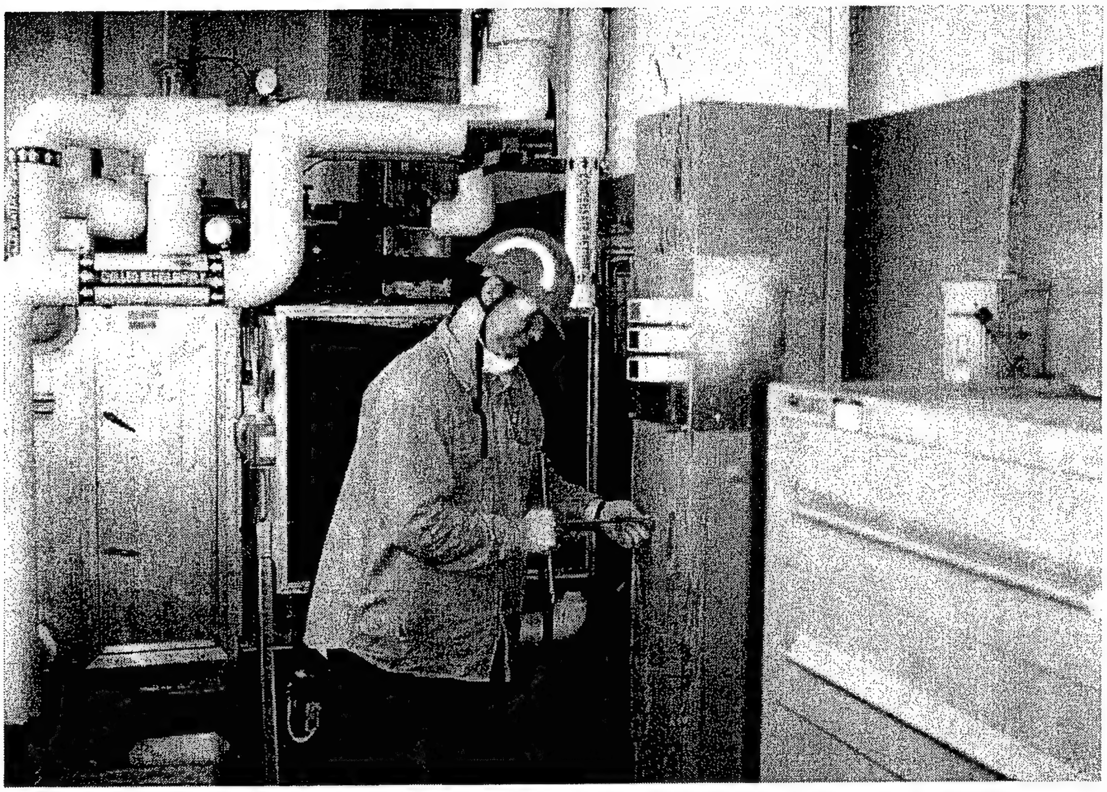


Figure 35. Extracting cores with an incrememt borer to detect rot.

6.2.2.4 Sonic Evaluation

Several sound-driven inspection methods, including sonic wave velocity, acoustic emission, and stress wave analysis, have been investigated. The simplest of the sonic techniques uses an instrument to measure velocity changes of a sound wave moving across the wood (Figure 36). This testing device utilizes two probes pressed against opposite sides of a pole to detect internal voids, which may or may not be decay (Graham and Helsing 1979). Tripping a hammer sends a sound wave down one probe, through the wood, and up the other probe to an indicator dial. A low reading compared with that for sound wood of similar dimension indicates decay or a void such as a ring shake. The device is said to work well on Douglas Fir and western red cedar but, apparently, not as well on southern pine.

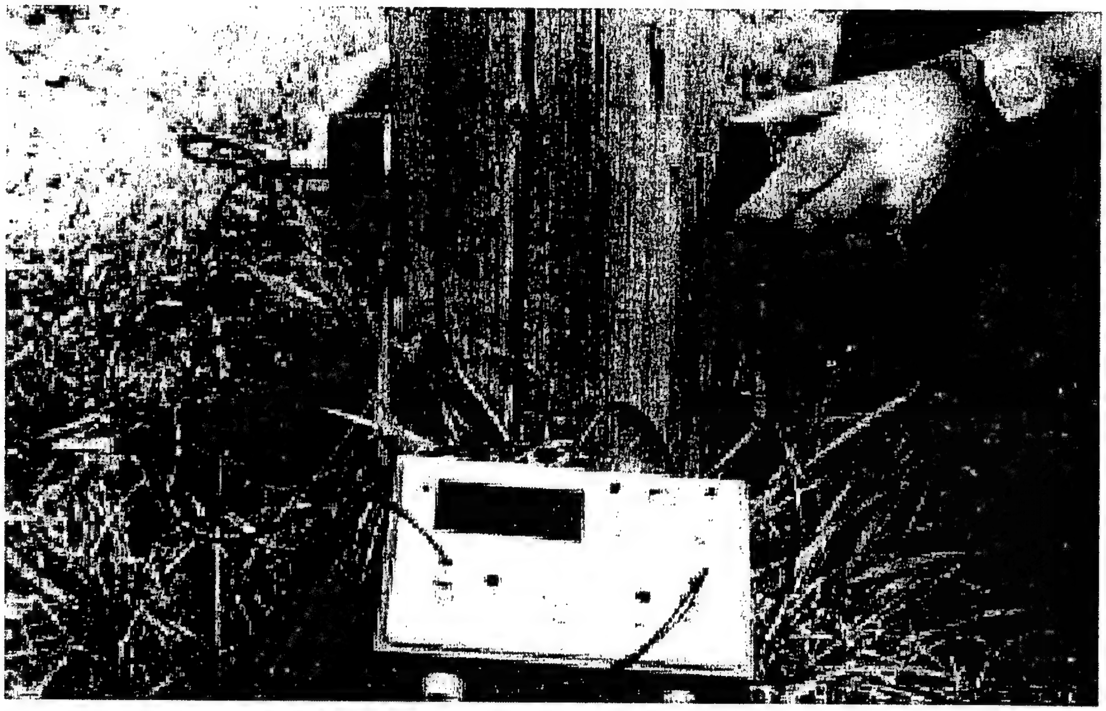


Figure 36. One example of a sonic inspection device for detecting internal defects in wood

An ultrasonic device used for detection of internal decay (Gerhards 1978) and damage from insects or marine organisms (Agi 1976) is the James "V" meter (James Instruments, Inc., Chicago, IL). The ultrasonic equipment consists of a transmitter, receiver, and instrumentation to measure sound transmission time in microseconds. The equipment generates ultrasonic pulses at regular intervals of time and measures the time of flight between transducers. The presence of voids, decay, soft pockets of wood, and other discontinuities within the cross-section are readily indicated by a higher required sonic transmission time. The test method requires a grid to be drawn on opposite sides of the questionable member and readings taken at the grid intersections (Figure 37). Typically, a 4 or 6 in. square grid is used. The device is nondestructive and proven to be effective on Douglas Fir and southern pine.

6.3 Inspection Procedures

Inspection procedures for timber structures are affected by such variables as age, type of structure, onsite environment. In general, the inspector must thoroughly examine the structure for decay and other deterioration, and record findings in sufficient detail for an engineering assessment. The specific procedures and methods, however, will vary substantially from structure to structure. Appendix A provides some helpful background engineering information for less-experienced inspectors, and Appendix B shows examples of useful inspection forms.

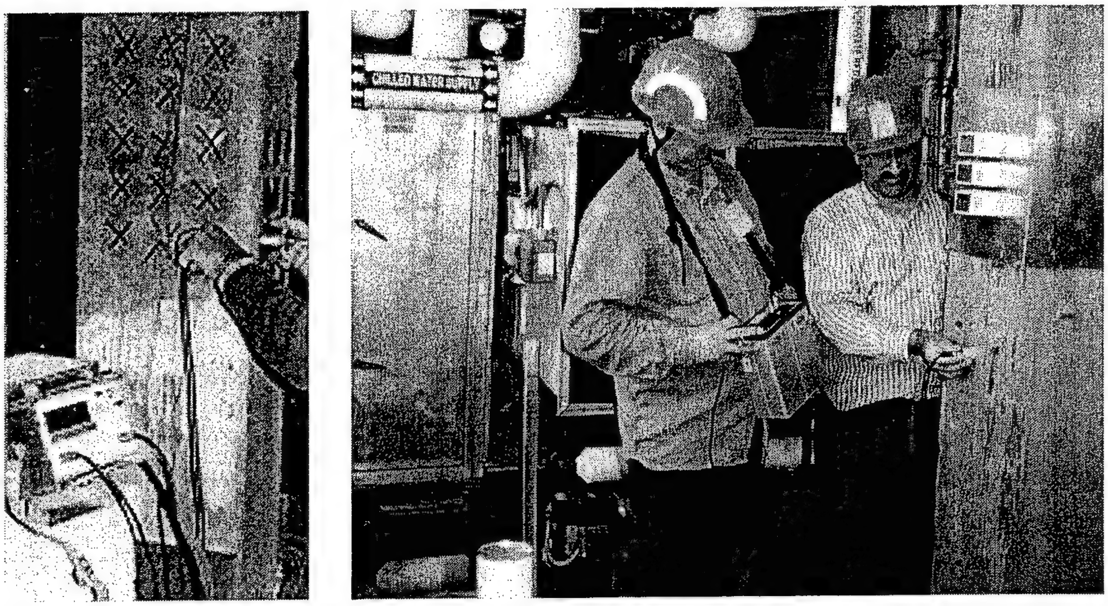


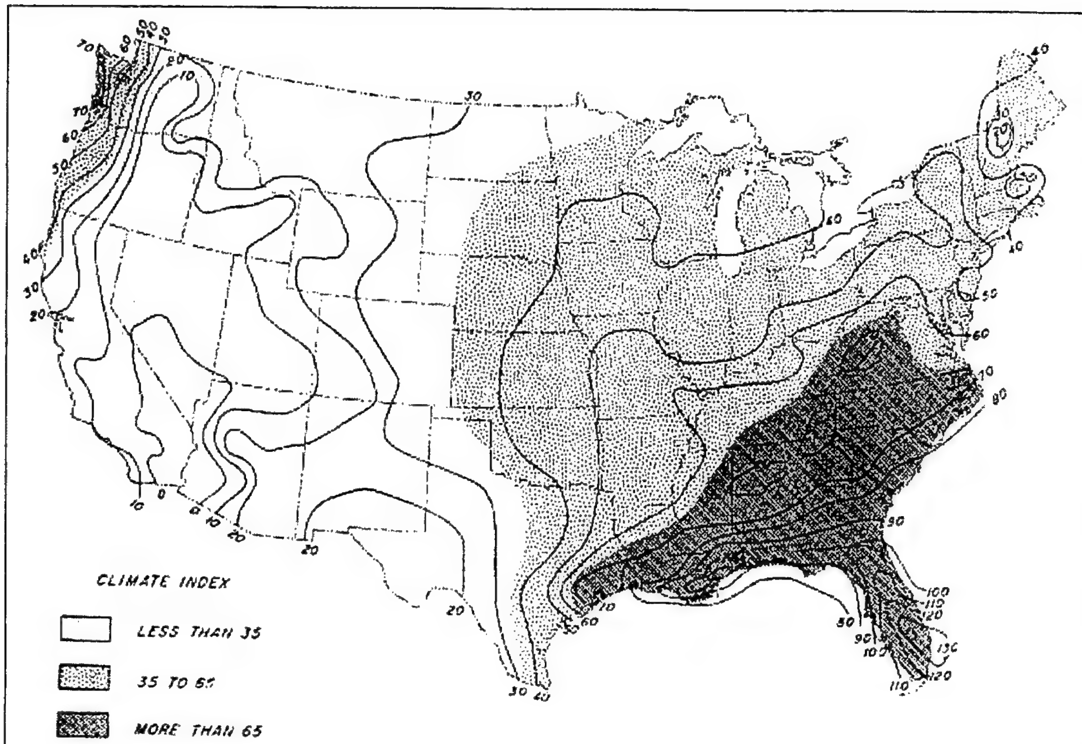
Figure 37. Using a V meter for nondestructive ultrasonic inspection of internal wood condition.

6.3.1 Pre-Inspection Procedures

Pre-inspection procedures involve the review of information prior to field inspection. The purpose of the review is to learn as much as possible about the history of the structure to better prepare the inspector for the field work.

Previous inspection reports are one of the best sources of information. These reports provide the most current information on the condition of the structure and familiarize the inspector with the types and locations of previous damage. In addition, the original construction drawings and documents are good sources of information. As-built drawings are most informative, but when they are not available, design drawings may be used. Design drawings may lack specific detail about the individual structure, but they provide information about the dimensions, species, and grade of material used as well as the type and retention of preservative treatments.

When site-specific information is not available, the general potential for fungal attack can be correlated geographically based on variations in average rainfall and temperature. Maps are available that depict insect and decay hazards based on climatic conditions across broad regions (Figure 38); however, local conditions within these regions may vary considerably.



Darkest areas: wettest climates, most suitable for decay; index greater than 65
Lightest areas: driest climates, least suitable for decay; index less than 35
Gray areas: moderately wet climates, moderately suitable for decay organisms; index 35 to 65

Reference, Ritter, M.A., Timber Bridges: Design, Construction, Inspection, and Maintenance, USDA, Forest Service, 1992.

Figure 38. Levels of decay potential for wood exposed to the weather in aboveground service based on a climate index derived from standard temperature and rainfall data.

6.3.2 Individual Component Inspection

Field inspection is the physical examination of a structure for deterioration. It is necessary for the inspector to be well familiar with the forms of deterioration, the areas conducive to decay, and the fundamentals of individual component inspection.

Component inspection involves the systematic examination of individual construction members. When deterioration is found, its location and extent must be defined and noted so that the load-carrying capacity of the structure can be determined by engineering analysis. At some locations, deterioration may have no significant effect on member strength. In other locations, any deterioration will reduce capacity. In both cases, the inspector must accurately locate, define, and record all deterioration.

Regardless of structure size, no inspection can reasonably or economically examine every individual component. However, the inspector must base the degree of inspection on the information gathered from the pre-inspection evaluation and knowl-

edge of structure deterioration, as well as the causes, signs, and probable locations of the deterioration.

Individual members should be checked for grade stamps or other evidence of quality to be sure that the grade of the material conforms with previously obtained drawings and specifications. If there are no drawings or specifications for comparing the information is still needed as a basis for analysis of the load-carrying capacity of the members. Lacking grade marks, members should be examined for knots, cross grain, checks and shakes, and other strength-related factors to determine whether they are cause for concern.

Seasoning checks are to be expected in solid sawn members of large cross section because of dimensional changes during drying, since it is impractical to dry them to service moisture content prior to installation. If these cracks are too deep, they may seriously reduce shear and tensile strength. If they extend completely through the thickness of a member, they may cause excessive deflection. Also deep cracks may extend below the treated shell of a timber and expose the untreated core to decay (Figure 39). Checks should always be related to those permitted in the given grade of wood because their presence does not necessarily indicate a defective beam.

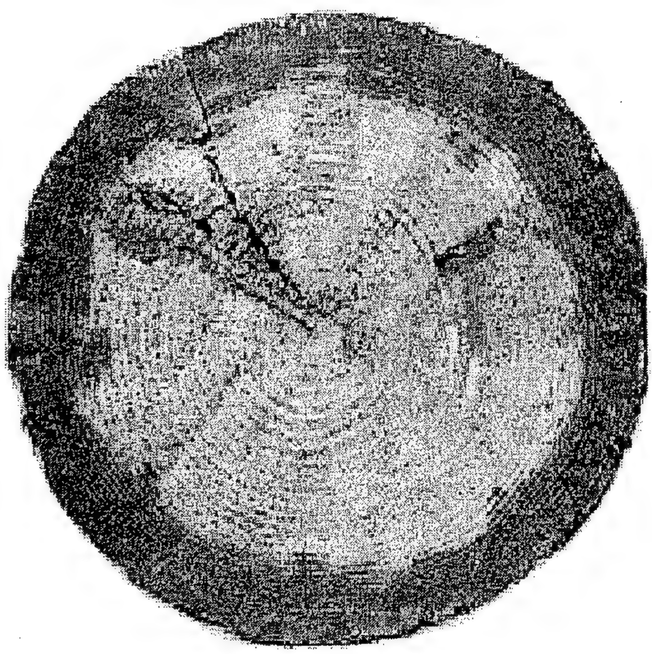


Figure 39. Deep seasoning check in Douglas Fir section.

Damage to a member warrants an effort to determine the type of stress that caused the damage and the fracture, if present. It is important to know whether the damage occurred during shipment or erection, or resulted from misalignment or miscut-

ting during fabrication, or deliberate alteration (perhaps by a tradesperson) after it was put in place, or the supports settled, or the loads exceeded design specifications, or the connections loosened or failed. The cause of the damage must be taken into account if repair is to be effective.

6.3.3 Records and Reports

After recording all information pertaining to the decay and wood damage detected during the inspection process, reports are prepared. These repairs provide the principal means of communicating condition information about the structure. The purpose of this documentation is to identify conditions that may limit the capacity of the structure or otherwise make it unsafe for public use, develop a chronological record of structural condition, provide the information necessary to complete a structural analysis when conditions change, provide a basis for identifying current and future maintenance needs through the early detection of early structural deficiencies, and provide a reference source for future inspections and comparative analysis.

A good inspection report documents detected deterioration and notes any details of the structure that deviate from the as-built drawings. During the course of the inspection, these deficiencies should be noted as they are found in order to avoid loss of detail. The inspector should be as objective as possible, recording what is seen and measured.

Sketches, drawings, and photographs are extremely important for illustrating the inspection results. Drawings and sketches should define the location and extent of deterioration in sufficient detail and accuracy so that other inspectors or maintenance personnel can easily locate the area in question. Photographs are also very useful for showing details of structure condition and areas of deterioration.

6.4 Rating

The inspection process should produce a rating for the condition of each structural member. A rating scale of 0 – 9 is recommended, with 9 indicating new or excellent condition and 0 signifying critical condition. A typical wood truss inspection report format is presented in Figure 40, including definitions for the numerical ratings.

TIMBER STRUCTURE INSPECTION REPORT

Building No.________________ Building Size Truss Span

Date of Inspection____________ Building Age History of Use

Inspection Team

Department

STRUCTURAL COMPONENT CONDITION RATING

Member No.	Rating: 0 – 9								
	Deflection	Column condition	Connection problems	Splits	Fracture	Decay	Insect damage	Overall rating	Comments

CONDITION RATING DEFINITIONS

N Not applicable
9 New or in excellent condition
8 Good condition; no repairs needed
7 Generally good condition; minor maintenance may be necessary
6 Fair condition; major maintenance may be necessary
5 Generally fair condition; minor rehabilitation may be necessary
4 Marginal condition; major rehabilitation may be necessary
3 Poor condition; repair or rehabilitation required immediately
2 Critical condition; repair and rehabilitation is urgent and facility must be closed for repairs
1 Critical condition; facility must be closed and a feasibility study for repair is conducted
0 Critical condition; facility must be closed or demolished

Figure 40. Sample condition rating form for wood trusses.

Maintenance Consideration: Maintenance should be considered when there is evidence of a decay hazard such as water stains, or surface molds indicating the presence of free water or high humidity levels.

Maintenance Required: Maintenance is required when some localized decay or insect infestation is evident, or connectors have become loose; slight deflections may be observed.

Immediate Repair: This condition may be indicated by noticeable deflections, critical areas of decay, or termite damage.

Unsafe Condition: The structure is considered unsafe where there are localized failures, severe decay or termite damage, or severe displacement of members.

Overall Rating: The lowest rating of any distress condition is considered to be the overall rating of the structural member under inspection.

Special Criteria for Adjacent Members: Special consideration must be given to adjacent members where the overall rating of the structure will be reduced based on the lowest rating of each individual member.

6.5 Code Changes Spanning 1944 – 1991

The *National Design Specification for Wood Construction* (NDS) was first published in 1944 by the National Lumber Manufacturers Association (currently the American Forest and Paper Association) under the title *National Design Specification for Stress-Grade Lumber and Its Fastenings*. The NDS has gone through some significant changes, including issues related to sawn lumber trusses such as general design requirements, modifications to design values and lumber sizes. The code years covered include 1944, 1971, 1973, 1977, 1982, 1986, and 1991.

6.5.1 General Design Requirements

The 1944 NDS was based on allowable stress design using elastic stress-strain theory for calculating the stresses. This design procedure has remained unchanged from the original edition of the code. The scope of the NDS has changed over the years, however, along with some general design requirements. These design requirements include lumber designations, design loads, and normal service conditions.

The NDS code divides sawn lumber into three categories: joists and planks, beams and stringers, and posts and timbers. These designations were changed over the years, as shown in Table 12.

Throughout the history of the NDS code, no load combinations have been prescribed. Rather, it states that the design loads are to be the most severe distribution, concentration, and combination of dead, live, snow, wind, earthquake, erection, and other static and dynamic forces. The only guidance that the code gives is that the probabilities of the full wind and full snow loads or the full wind and full earthquake loads acting simultaneously are remote. The code also states that the magnitudes of the loads shall be in accordance with the governing building code. These provisions have remained unchanged since the original 1944 edition of the code.

The material properties of wood are very sensitive to the specific temperature, moisture condition, load duration, and type of pressure treatment. Therefore, the design values must be assigned with respect to normal conditions of use, utilizing modifica-

tions for other service conditions. These normal conditions of use are defined as shown in Table 13.

Table 12. Lumber designation changes.

Code Year	Lumber Designation	Requirements
1944	Joists and Planks	rectangular cross-section from 2" to 5" thick, and ≥ 4" wide
	Beams and Stringers	rectangular cross-section ≥ 5" thick, ≥ 8" wide, and graded with respect to bending when loaded on the narrow face
	Posts and Timbers	approximately square cross-section ≥ 5" x 5" and graded with respect to longitudinal loading where bending strength not critical
1971	Dimension Lumber	rectangular cross-section from 2" to 5" thick, and ≥ 2" wide
	Beams and Stringers	same as 1944
	Posts and Timbers	same as 1944
1973	same as 1971	
1977	Dimension Lumber	rectangular cross-section from 2 in. to 4 in. thick, and ≥ 2" wide
	Beams and Stringers	rectangular cross-section ≥ 5" thick, width more than 2" greater than thickness, and graded with respect to bending when loaded on the narrow face
	Posts and Timbers	approximately square cross-section ≥ 5" x 5", with width not more than 2" greater than the thickness, and graded with respect to longitudinal loading where bending strength not critical
	Decking	from 2 in. to 4 in. thick, and ≥ 6" wide, tongued and grooved or grooved for a spline on the narrow face
1982	same as 1977	
1986	same as 1977	
1991	Dimension Lumber	same as 1977
	Beams and Stringers	same as 1977
	Posts and Timbers	same as 1977
	Decking	from 2 in. to 4 in. thick, tongued and grooved or grooved for a spline on the narrow face

Table 13. Code changes with respect to normal conditions of use.

Code Year	Normal Conditions of Use
1944	For lumber continuously dry (as in most covered structures), pressure-impregnated by an approved process and preservative, and subjected to long-term (permanent) loading
1971	Included a modification for lumber pressure-impregnated with fire-retardant chemicals and the tabulated design values are valid with respect to lumber not fire treated; the assumptions of normal loading duration and normal moisture conditions were also modified; normal loading duration is a load that stresses the member to its full design value and has a duration of approximately 10 years (continuously or cumulatively); normal moisture condition was quantitatively defined for each specific wood species and grade, although the vast majority assume a member surfaced dry or green and used at a 19% moisture content
1973	Same as 1971
1977	The effect of temperature was taken into account and the NDS stated that the design values were valid for normal temperature fluctuations and occasional, short-term heating up to 150 °F; the normal moisture condition was more specifically defined as (1) an in-use moisture content ≤ 19% regardless of the type of sawn lumber and the moisture content at the time of manufacture, or (2) an in-use moisture content ≤ 15% applicable to 2 in. to 4 in. thick sawn lumber manufactured at a moisture content ≤ 15%
1982	Same as 1977
1986	Same as 1977
1991	Mostly unchanged; summarized as follows: (1) Temperature: normal temperature fluctuations and occasional, short-term heating up to 150 °F (2) Moisture Condition: an in-use moisture content ≤ 19% regardless of the type of sawn lumber and the moisture content at the time of manufacture (3) Load Duration: a load that stresses the member to its full design value and has a duration of approximately 10 years (continuously or cumulatively) (4) Wood Preservative Treatment: a member pressure-impregnated by an approved process and preservative (5) Fire Retardant Treatment: a member not treated with fire retardant chemicals

6.5.2 Modifications to Design Values

The most significant changes to the NDS apply to the various modifications to the tabulated design values, i.e., general modifications relating to the conditions of use. The NDS cites the load duration adjustments that are correlated to specific load cases, as shown in Table 14.

In 1991, several major changes were made to the adjustment factors in addition to a more understandable system for the applicability of these adjustment factors. The applicability of the adjustment factors to the design values is summarized in Table 15. A brief discussion of each adjustment factor follows the table.

Code Year	Load Case	Adjustment Factor
1973	For Redwoods: Compression parallel to grain Modulus of elasticity Shear as applied to joint details with mechanical fasteners at a distance greater than 5 times the depth from end of member	 1.15 1.04 1.50
1977	0% moisture content, cooling below 68°F: for modulus of elasticity for other design values	 +0.04%/°F +0.17%/°F
	0% moisture content, heating above 68°F: for modulus of elasticity for other design values	 -0.04%/°F -0.17%/°F
	12% moisture content, cooling below 68°F: for modulus of elasticity for other design values	 +0.14%/°F +0.32%/°F
	12% moisture content, heating above 68°F: for modulus of elasticity for other design values	 -0.19%/°F -0.49%/°F
1982	12% moisture content, cooling below 68°F: for modulus of elasticity	 +0.15%/°F
	12% moisture content, heating above 68°F: for modulus of elasticity	 -0.21%/°F
1986	0% moisture content, cooling below 68°F: for modulus of elasticity, tension parallel to grain for other design values and fasteners	 +0.09%/°F +0.14%/°F
1986	0% moisture content, heating above 68°F: for modulus of elasticity, tension parallel to grain for other design values and fasteners	 -0.11%/°F -0.19%/°F
	12% moisture content, cooling below 68°F: for modulus of elasticity, tension parallel to grain for other design values and fasteners	 +0.13%/°F +0.24%/°F
	12% moisture content, heating above 68°F for modulus of elasticity, tension parallel to grain for other design values and fasteners	 -0.13%/°F -0.38%/°F
	24% moisture content, cooling below 68°F: for modulus of elasticity, tension parallel to grain for other design values and fasteners	 +0.38%/°F +0.84%/°F
	24% moisture content, heating above 68°F: for modulus of elasticity, tension parallel to grain for other design values and fasteners	 -0.15%/°F -0.57%/°F
	Lumber pressure impregnated with fire retardant chemicals: Extreme fiber in bending Tension parallel to grain Horizontal shear Compression perpendicular to grain Compression parallel to grain Modulus of elasticity Fastener design loads	 0.85 0.80 0.90 0.90 0.90 0.90 0.90
1991	The load duration adjustment factors remained unchanged except for wind and earthquake loading	1.60
	The adjustment factor for moisture service condition was simplified to provide for two distinct situations, dry or wet; similarly, the adjustment factor for temperature service conditions was simplified to reflect specific temperature ranges; the adjustment factor for members pressure impregnated with fire retardant chemicals was no longer quantified, but rather, the designer was referred to the chemical manufacturer for the effect on the design values	

* Applies if the stresses induced by impact loads are less than the design values for permanent loads and Impact + Dead + Long-Term Live and/or Short-Term Live are less than twice the design values for permanent loads.

Table 15. Various design values.

Condition	Tabulated Design Values	Load Duration Factor	Wet Service Factor	Temp. Factor	Beam Stability Factor	Size Factor	Flat Use Factor[1]	Repetitive Use Factor[2]	Form Factor	Column Stability Factor	Shear Stress Factor	Buckling Stiffness[3] Factor	Bearing Area Factor
Extreme fiber in bending	F_b	C_D	C_M	C_t	C_L	C_F	C_{fu}	C_r	C_f	•	•	•	
Tension parallel to grain	F_t	C_D	C_M	C_t	•	C_F	•	•	•	•	•	•	•
Horizontal shear	F_V	C_D	C_M	C_t	•	•	•	•	•	•	C_H	•	•
Compression perpendicular to grain	$F_{c\perp}$	•	C_M	C_t	•	•	•	•	•	•	•	•	C_b
Compression parallel to grain	F_c	C_D	C_M	C_t	•	C_F	•	•	•	C_P	•	•	•
Modulus of elasticity	E	•	C_M	C_t	•	•	•	•	•	•	•	C_T	•
Fastener design loads	F_g	C_D	•	C_t	•	•	•	•	•	•	•	•	•

[1] The flat use factor (C_{fu}) applies only to dimension lumber bending members 2 in. to 4 in. thick.

[2] The repetitive member factor (C_r) applies only to dimension lumber bending members 2 in. to 4 in. thick.

[3] The buckling stiffness factor (C_T) applies only to 2" x 4" or smaller sawn lumber truss compression chords subjected to combined flexure and axial compression when 3/8" or thicker plywood sheathing is nailed to the narrow face.

Load Duration Factor (C_D)

The tabulated design values are based on a member fully stressed to its allowable design value for a cumulative duration of 10 years. For other conditions, the design values shall be multiplied by the following duration factors:

Load Duration	C_D	Typical Design Loads
Permanent	0.9	Dead Load
10 years	1.0	Occupancy Live Load
2 months	1.15	Snow Load
7 days	1.25	Construction Load
10 minutes	1.6	Wind/Earthquake Load
Impact	2.0	Impact Load

Wet Service Factor (C_M)

The tabulated design values are based on lumber used under dry service conditions with a maximum moisture content of 19%. For other conditions, the design values shall be multiplied by the following wet service factors:

F_b	F_t	F_v	$F_{c□}$	F_c	E
0.85 when $(F_b)(C_F)$ □ 1150 psi, $C_M = 1.0$	1.0	0.97	0.67	0.80 when $(F_b)(C_F)$ □ 750 psi, $C_M = 1.0$	0.90

Temperature Factor (C_t)

The tabulated design values are based on lumber used under ordinary ranges of temperature and occasionally heated in use to temperatures up to 150 ¬F. For lumber experiencing sustained exposure to elevated temperatures up to 150 °F, the design values shall be multiplied by the following temperature factors:

Design Values	In Service Moisture Conditions	C_t		
		T □ 100 °F	100 °F □ T □ 125 °F	125 °F □ T □ 150 °F
F_t, E	Wet or Dry	1.0	0.9	0.9
F_b, F_v, F_c, and $F_{c□}$	Dry	1.0	0.8	0.7
	Wet	1.0	0.7	0.5

Beam Stability Factor (C_L)

The tabulated design values shall be multiplied by the beam stability factor, C_L, as specified in the design provisions for bending. The beam stability factor, C_L, is defined as follows (somewhat different from the previous code):

- If the depth of a bending member does not exceed its breadth, $d \le b$, no lateral support is required and $C_L = 1.0$.
- When rectangular sawn lumber bending members are laterally supported in accordance with the requirements stated previously in the sawn lumber section of the code, $C_L = 1.0$.
- When the compression edge of a bending member is supported throughout its length to prevent lateral displacement, and the ends at points of bearing have lateral support to prevent rotation, $C_L = 1.0$.

The slenderness ratio is calculated as follows:

$$R_B = \sqrt{\frac{\ell_e d}{b^2}} \le 50$$

where ℓ_e is the effective length. The beam stability factor is then calculated as:

$$C_L = \frac{1 + \left(F_{bE}/F_b^*\right)}{1.9} - \sqrt{\left(\frac{1 + \left(F_{bE}/F_b^*\right)}{1.9}\right)^2 - \frac{F_{bE}/F_b^*}{0.95}}$$

where:

F_b^* = tabulated bending design value multiplied by all applicable adjustment factors except C_{fu}, C_H, and C_L

F_{bE} = $K_{bE}\, E'/R_B^2$

K_{bE} = 0.438 for visually graded lumber and machine evaluated lumber

K_{bE} = 0.609 for products with $COV_E \leq 0.11$

Size Factor (C_F)

When the depth of a rectangular sawn lumber bending member 5 in. or thicker exceeds 12 in., the bending design value, F_b, shall be multiplied by the following size factor:

$$C_F = (12/d)^{1/9} \leq 1.0$$

For dimension lumber 2 in. to 4 in. thick, the size factor corresponding to the applicable design values is as follows:

		F_b		F_t	F_c
Grades	**Width**	**Thickness**			
		2 in. & 3 in."	**4 in.**		
Select Structural, No. 1 & Btr. No. 1, No. 2, No. 3	2", 3", & 4"	1.5	1.5	1.5	1.15
	5"	1.4	1.4	1.4	1.1
	6"	1.3	1.3	1.3	1.1
	8"	1.2	1.3	1.2	1.05
	10"	1.1	1.2	1.1	1.0
	12"	1.0	1.1	1.0	1.0
	14" & wider	0.9	1.0	0.9	0.9
Stud	2", 3", & 4"	1.1	1.1	1.1	1.05
	5" & 6"	1.0	1.0	1.0	1.0
Construction & Standard	2", 3", & 4"	1.0	1.0	1.0	1.0
Utility	4"	1.0	1.0	1.0	1.0
	2" & 3"	0.4	N/A	0.4	0.6

Flat Use Factor (C_{fu})

When sawn lumber 2 in. to 4 in. thick is loaded on the wide face, the bending design value, F_b , shall be permitted to be multiplied by the flat use factor, C_{fu}, as follows:

Width	Thickness	
	2 in. & 3 in.	4 in.
2 in. & 3 in.	1.0	N/A
4"	1.1	1.0
5"	1.15	1.05
6"	1.15	1.05
8"	1.15	1.05
10 in. & wider	1.2	1.1

Repetitive Use Factor (C_r)

Dimension lumber 2 in. to 4 in. thick used as joists, truss chords, rafters, studs, planks, decking, or similar members that are in contact or spaced no more than 24" on centers, are not less than 3 in number, and are joined by floor, roof, or other load distributing elements adequate to support the design load, shall be multiplied by the repetitive use factor, C_r = 1.15.

Form Factor (C_f)

The form factor (for round or diamond-shaped beams) carries over with no change.

Column Stability Factor (C_P)

The tabulated design values shall be multiplied by the column stability factor, C_P, as specified in the design provisions for columns. Calculation of the allowable compression design values for solid columns relies on the determination of the column stability factor, C_P, which is calculated as follows:

- $C_P = 1$ if both edges are supported to prevent lateral displacement along the member's entire length.
- $C_P = \frac{1+\left(F_{cE}/F_c^*\right)}{2c} - \sqrt{\left(\frac{1+\left(F_{cE}/F_c^*\right)}{2c}\right)^2 - \frac{F_{cE}/F_c^*}{c}}$

where:

F_c^* = tabulated compression design values multiplied by all applicable adjustment factors except C_P
F_{cE} = $K_{bE}\, E'/(\ell_e/d)^2$
K_{cE} = 0.3 for visually graded lumber and machine-evaluated lumber (MEL)
K_{cE} = 0.418 for products with $COV_E \leq 0.11$
c = 0.8 for sawn lumber

0.85 for round timber piles
0.9 for glued laminated timber

Shear Stress Factor (C_H)

The calculated shear stress, f_v, in a bending member shall not exceed the allowable design value for shear parallel to grain, F_v'. The shear stress factor, C_H, is determined as follows:

Length of split on wide face of 2 in. (nominal) lumber	C_H	Length of split on wide face of 3 in. (nominal) and thicker lumber	C_H	Size of shake in 2 in. (nominal) and thicker lumber	C_H
no split	2.00	no split	2.00	no split	2.00
½ x wide face	1.67	½ x wide face	1.67	½ x wide face	1.67
¾ x wide face	1.50	¾ x wide face	1.50	¾ x wide face	1.50
1 x wide face	1.33	1 x wide face	1.33	1 x wide face	1.33
1½ x wide face or more	1.00	1½ x wide face or more	1.00	1½ x wide face or more	1.00

If $f_v > F_v'$, $C_H = 2.0$.

Buckling Stiffness Factor (C_T)

When two 2 x 4 or smaller sawn lumber truss compression chord is subjected to combined flexure and axial compression under dry service condition, and 3/8 in. or thicker plywood sheathing is nailed to the narrow face of the chord in accordance with good nailing practice, the tabulated modulus of elasticity design value, E, shall be permitted to be multiplied by the buckling stiffness factor, C_T:

- when □e □ 96 in., C_T is calculated as follows:

$$C_T = 1 + \frac{K_M \, \ell_e}{K_T \, E}$$

where:

K_M = 2300 for wood seasoned to 19% moisture content at time of attachment to sheathing
K_M = 1200 for wood unseasoned or partially seasoned at time of attachment
K_T = 0.59 for visually graded lumber and MEL
0.82 for products with COV_E □ 0.11

- when □e > 96 in., C_T shall be calculated based on ℓ_e = 96in.

Bearing Area Factor (C_b)

The tabulated design values perpendicular to grain, $F_{c\perp}$, apply to bearing of any length at the ends of a member and to all bearings 6 in. or more in length at any other location. For bearings less than 6 in. long and not nearer than 3 in. to the end of a member, the tabulated compression design value perpendicular to grain shall be permitted to be multiplied by the following bearing area factor, C_b (this factor was present in the previous code, but it did not have a name):

$$C_b = \frac{\ell_b + 0.375}{\ell_b}$$

where $\square_b$ is the length of bearing.

6.6 Inspection of Specific Structural Types

Many aspects of inspection are common to several types of structures. Unusual loadings, whether they be on a bridge, a heavy truss, or on a factory floor should be considered carefully with respect to the original design. Likewise, any structure that has been exposed to fire or to high temperature should be examined for the effects of such exposure even though it is not prescribed specifically in connection with the inspection of a specific structural type.

6.6.1 Heavy Timber Buildings

6.6.1.1 Checking

Many older timber buildings were constructed with large solid timbers for beams, girders, columns, and truss members. Because such timbers characteristically have dried in place, large checks are common. Their location and depth should be measured to determine whether they might have serious effects on load-carrying capacity and whether the defects exceed the limits permitted by current grading rules. In beams, for example, are the checks severe enough to seriously reduce shear strength? In columns, are they sufficiently severe to cause the column to behave as if it were made of multiple pieces, with sharply increased values of length/least dimension and sharply reduced load-carrying capacity?

6.6.1.2 Evidence of Water

Watermarking or other evidence of the presence of liquid water from condensation, roofing or plumbing leaks, or periodic flooding should be noted. Special attention should be paid to areas of the structure where drainage is poor or nonexistent, where ventilation is poor, or where condensation can occur. Moisture meter readings should be taken and evidence of decay looked for in such locations.

6.6.1.3 Mechanical Damage

Mechanical damage may have occurred during timber shipment or construction, from cutting by tradespeople, and from other causes. The damage should be identified and its effects evaluated. Damage may range from split-off corners or fractures to columns knocked off their base anchorage and seriously out of plumb. Members in areas adjacent to vibrating machinery may have checks or other damage accentuated and extended by vibrations and, in addition, fasteners may have loosened.

6.6.2 Heavy Trusses

Older trusses were commonly constructed of solid sawn timber made up of two or more members with the webs and chords occupying separate planes to permit web/chord connections where the members overlap. Inspection for bolt tightness is particularly important in such trusses because the potential for shrinkage may promote the loosening of bolts.

6.6.2.1 Truss Bracing

Trusses must be properly braced to be structurally viable. Erection bracing, commonly X-bracing between trusses, lower-chord struts in line with the X-braces, and top-chord joists or roof sheathing comprise the primary bracing elements. Stability of the compression chord is particularly important and should be a prime concern in the inspection, with particular attention given to areas where the roof diaphragm is not in the plane of the compression chord, as in the case of a raised skylight or dormer. Unless otherwise braced in such areas, there is a potential for buckling of the compression chord.

6.6.2.2 Truss Connections

Older trusses may have connections with little or no hardware, such as compressive web members notched into chords, leaving the potential for dislocation. Also in

such connections, shear area may be inadequate, and evidence of excessive deformation as a result of shear failure should be looked for.

Bolted joints at the areas of overlap between members commonly involve eccentricity when the axes of webs and chords do not intersect at a common point. Web-chord connections and the members entering such connections should be examined for evidence of distress as a result of eccentricity.

Splices in the lower chord and connections at the heel joint are critical since the entire lower-chord tensile force must be taken at these connections. Thus they need careful examination to be sure that the bolts are tight, that there is no unusual deformation, and that there is no fracture at bolt holes.

Allowable connector loads (as well as allowable design stresses for wood members) were more or less arbitrarily increased as a material conservation measure during World War II. As a consequence, some connections may be overstressed and show distress. Connections — particularly lower-chord splices and heel joints — should be examined for evidence of excessive deformation.

6.6.3 Light Trusses

Design of light trusses employing metal truss plates as connections between members at a joint is somewhat specialized. It is desirable to contact the engineer who originally designed the trusses or the manufacturer of the truss plates to ensure that all background information related to design and use is known.

6.6.3.1 Lumber Grade

The grade of lumber in the various truss members may be determined from grade stamps on the lumber. Lacking a grade stamp, or if there is a question about the accuracy of the grade, each member may be regraded according to the appropriate grading rules.

6.6.3.2 Moisture Condition

Evidence of current or past moisture problems resulting from roof or plumbing leaks, inadequate vapor barriers, or other sources should prompt careful examination of truss members for signs of decay and a check of the moisture content by means of a moisture meter.

6.6.3.3 Connections

Connections between truss members may be of any of a number of types — split rings or shear plates in conjunction with bolts. If split rings or shear plates have been used, the tightness of the bolts should be checked, and the joint should be examined to be sure that the connectors are actually present, particularly if there is evidence of unusual deformation in the joint. All connections joined with nails, bolts, or plates should be carefully checked for corrosion, especially when there is evidence of unusually moist conditions or when the wood is known or thought to have been treated with a salt-based fire retardant or preservative.

6.6.3.4 Damage

Members and connections should be checked for evidence of mechanical damage during fabrication, erection, or use. Although it is probable that most damage occurs during fabrication and site handling, it is possible that members have been cut to accommodate some unplanned feature such as a fireplace, an attic stairway or new mechanical equipment. Ends of members should be checked for splits that may have occurred in handling but which may also be the result of moisture change.

6.6.3.5 Deformation

Warped or bowed members may cause movement of the truss. This may create a phenomenon called ceiling-floor-partition separation (Forest Products Research Society 1979) which manifests itself as a separation either at the junction of the ceiling and the partition or at the junction of the partition and the floor in light frame construction. Such separation also may occur from other causes, including: (a) improper construction of walls, floors, partitions, and foundations, which can result in differential settlement; (b) use of wet wood in the floor system, which can result in excessive shrinkage; (c) frost heaving or expansive soils, which raise the exterior walls; and (d) attachment of bottom chords of trusses to interior partitions.

6.6.4 Bridges

Bridges, like other heavy timber structures, should be checked for quality and soundness of members and connections. Because of their exposure to the weather, however, they are especially subject to prolonged exposure to water and thus to the hazard of decay. The members are usually pressure-treated with preservative.

6.6.4.1 Moisture and Decay

The structure should be examined for visual evidence of conditions conducive to decay. Bearing areas between deck and girders, between girders and pile caps or abutments, or pile caps and piles should be carefully examined. Even in arid or semi-arid regions there is risk of decay, especially around end grain where dirt accumulates and retains moisture from dew or occasional rain.

6.6.4.2 Mechanical Damage

All portions of the bridge, both superstructure and substructure, should be examined for mechanical damage. On highway bridges built with through trusses, for example, all members — but especially the end posts — are subject to damage from impact by vehicles. Bent piles are subject to impact by ice and debris and, depending on the nature of traffic in the river, by boats or ships.

6.6.5 Pole Structures

6.6.5.1 Condition Above Ground

Poles should be examined for general condition, unusual damage (including mechanical damage as from vehicle impact), and the size and location of seasoning checks. Even narrow checks may penetrate deeply into the poles, exposing untreated heartwood to the hazard of decay. Look for round or elliptical holes made by beetles, for mounds of sawdust and the carpenter ants that make them, for woodpecker holes, and for evidence of attack by termites (Graham and Helsing 1979).

6.6.5.2 Sounding

Poles should be sounded from as high as can be reached down to the groundline in order to locate suspicious areas that should be cored or drilled. If ultrasonic equipment is available, it should be used to locate areas of suspected decay (Graham and Helsing 1979).

6.6.5.3 Drilling and Coring

After sounding or other evaluation, suspect areas of the pole should be drilled or cored downward at an angle of about 45 degrees at the groundline, or slightly upward above ground so the hole drains downward to prevent water from collecting inside. Determine shell thickness and depth of preservative treatment. Poles that sound "good" should be drilled or cored at the groundline or, preferably, about a foot

below the groundline near or below the widest check. Then, if the wood is solid, the poles may be rated as "good" until cultures confirm or contradict the condition estimate. If rot is found, drill holes at third or quarter points around the circumference and measure shell thickness, depth of preservative treatment, and pole circumference. This information may be used to determine whether the pole should be replaced, retained in place, reinforced, or treated in place. Poles that sound suspicious should be drilled or cored in suspicious areas and near the widest check at or below groundline. If the shell is inadequate, schedule the pole for reinforcement or replacement. If the shell is adequate, remove cores at third or quarter points; depending on shell thickness, schedule the pole for replacement, stubbing, supplemental treatment, or reinspection (Graham and Helsing 1979).

6.6.5.4 Digging Inspection

Dig the pole out to a depth of 18 in. (in wet climates) and deeper (in dry climates). Clean the surface of dirt and examine for rot, probing suspicious areas for soft wood. Scrape the surface with a dull tool or shovel to remove all rotten wood. Drill or core the pole below the largest check to inspect for internal rot. If present, determine shell thickness and preservative penetration. Determine from this information what action should be taken (Graham and Helsing 1979).

7 Serviceability and Strength-Reduction Characteristics of Wood

This chapter presents guidelines on the serviceability of wood grades in light of their structural performance. Strength-reducing characteristics of each grade are addressed. A qualitative evaluation is presented to determine reduction in strength from the formation of splits of various orientations. Different scenarios of axial, moment, shear, and torsion loading are considered for various types of split orientations to approximate reduction in strength due to the presence of splits. The crushing strength of wood is an important characteristic in posts, columns, piles, truss chords, and web members of trusses subjected to compressive stress.

7.1 Factors Influencing Serviceability of Wood Structures

7.1.1 Loads

A timber structure must be designed in such a way as to provide adequate resistance to all loads that may reasonably affect safety and serviceability during its intended life. These include both applied loads and those resulting from natural hazards. Local building authorities specify the design loads to be used, either in their own building codes or by reference to national codes.

Structural members tend to creep under constant or repeated service loads, hence accumulating residual deformations, possibly necessitating a nonlinear structural analysis. Environmental factors can lead to a long-term reduction in load-carrying capacity as a result of shrinkage and splitting of members and possible loosening of connections. Efficient lightweight structural systems exhibit a high ratio of live load to dead load, and therefore they are sensitive to variations in live load as well as to uplift and overturning. Design for serviceability may be controlled by stiffness requirements in order to limit transverse deflections, lateral drift, and transmission of vibrations.

7.1.1.1 Applied Loads

Loads generally included under this category are the dead and live gravity loads, constraint forces, and accidental loadings such as from fire and blast. Forces due to accidental loads are usually accounted for indirectly through structural integrity requirements.

Dead load consists of the weight of the structure and permanently attached items. Live loads are related to the intended use of the structure as well as to occasional extraordinary loading situations. Additional considerations in the assessment of live loads include concentrated loads, impact, and live load reduction.

7.1.1.2 Natural Hazard Loads

Depending on geographical location, timber structure design generally recognizes forces that may be applied due to wind, snow, flood, earthquake, ponding, and expansive soil.

7.1.1.3 Wind

Since wind is not a static load, its dynamic forces may create unexpected stresses in a structure. A dynamic analysis or wind tunnel test may be advisable for a structure potentially sensitive to wind forces.

7.1.1.4 Snow

Snow loading is a function not only of geographical location but also of local terrain effects and structure geometry. Nonuniform loading due to drifting and to melting and ponding in deflected areas of flat roofs can be of significant importance.

7.1.1.5 Flood

Structural flood damage occurs predominantly at the anchorage system of a building. Calculations of buoyancy during flooding should be based on framing, sheathing, roofing, partitions, and finishings, plus 6 to 8 in. of air entrapment below each interior level. Flooding is often associated with high wind loads such as may occur in hurricanes, and this combination of wind and water action can result in extreme loadings of wood structures.

7.1.1.6 Ponding

Long-term creep under sustained load and potential environmental deterioration of timber structures are of special concern here, as water trapped in low spots can develop into roof leaks and lead to eventual decay of the wood roof deck.

7.1.1.7 Earthquakes

Points to be considered in seismic design include ductility in members and connections, limited strength loss with load reversal, compatible ductility between elements, and alignment of the mass and rigidity centers to avoid torsion.

7.1.1.8 Expansive Soil

The effects of expansive soil are especially important for timber structures because of their relatively light structural weight. Appropriate soil preparation and foundation design should be considered where the potential for this hazard exists.

7.1.1.9 Construction Overloads

Localized overloads may occur during construction. The most obvious one of these results from storing roof sheathing or other construction materials at concentrated locations, usually near a convenient location for lifting. Construction equipment which is used on a structural floor or roof may also cause excessive stress. The use of heavy machinery for placing aggregate on a built-up gravel roof or for placing earth on the roof of an earth structure are examples of this type of unusual loading.

7.1.1.10 Failure of Individual Elements

Overloading, if it causes overstress in any component of the structure, may reduce the structural integrity of that component, resulting in excessive stress on another component. This can in turn lead to eventual failure under what would normally be a safe load.

7.1.1.11 Anisotropic Nature of Wood

Timber has special characteristics which may induce stresses that are not usually anticipated. It is, also, orthotropic in nature, with different strengths in the three different directions — parallel to the fiber direction and perpendicular to it in directions both tangential and radial to the annual rings. Timber has its greatest strength in tension and compression parallel to the grain. Conversely, wood is rela-

tively weak in compression across the grain and is particularly so in tension across the grain. Thus an understanding of the directionally oriented strength characteristics of timber is important in evaluating its resistance to loading.

7.1.1.12 Shrinkage Effects

Wood shrinks with a decrease in moisture and swells with an increase in moisture content. This phenomenon must be accounted for in the design of a structure and in the planning of structural connections. Connections that will not permit free shrinking or swelling of wood may cause unanticipated stresses in the members being joined.

7.1.1.13 Eccentricity at Connections

Previous discussions point out that the assembly and fastening methods used for a timber structure can result in stresses and deformations that may not have been considered in the original design.

7.1.2 Duration of Load

Wood can withstand higher loads for a short period of time than it can for a long time period. The strength properties are stated as allowable stresses valid for loads acting over a period of 10 years. If the actual loads act for a period longer or shorter than 10 years, the designer should apply the adjustment factors shown in Table 16 to the allowable stresses.

Table 16. Duration-of-load adjustment factors used in structural design.*

Loading conditions	Adjustment factor
Continuous	0.90
10 years	1.00
2 months	1.15
1 week	1.25
1 minute	1.33
Impact	2.00

* American Society of Civil Engineers Committee on Wood, *Evaluation, Maintenance and Upgrading of Wood Structures: A Guide and Commentary*, 1982. The time period to be used is the time that the full design load acts on the structure either continuously or as the aggregate of shorter periods of full design load over the structure's life.

7.1.3 Temperature

As with all structural materials, changes in the temperature of wood will alter its mechanical properties. However, unlike inorganic materials, wood is significantly affected by duration of the temperature change if the temperature exceeds a critical

level. Mechanical properties are strongly correlated to the degree of thermal degradation which, in turn, is related to the temperature of the wood and the period during which it is maintained. Thermal degradation is reflected largely by the loss of wood mass at elevated temperatures. Therefore, mass loss is a sensitive indicator of mechanical property change.

The degree to which overall properties of a wood section undergo change further depend upon the temperature history of each point within the section and location of the wood fibers critical to the given loading condition. For example, the top and bottom of a beam contain wood fibers that respond rapidly to change in environmental temperature, thereby altering bending strength. On the other hand, a compression or tension member relies upon all wood fibers to carry load, so heating or cooling takes longer to alter the load-carrying capacity.

The properties at a given temperature are seen to exhibit recovery of or permanent damage to, levels achieved at room temperature (68 °F or 20 °C). The ratio of permanent to recoverable change generally increases with increasing temperature and duration of exposure. As temperatures decrease below comfortable room conditions (68 °F or 20 °C), the inverse is true; most properties increase and the levels at room temperature are fully recoverable.

Table 17 lists percentage changes in properties at –58 °F (-50 °C) and +122 °F (+50 °C) relative to those at 68 °F (20 °C) for a number of moisture conditions. The large changes at –58 °F (-50 °C) for wet wood (at the fiber saturation point or wetter) reflect the presence of ice in the wood cell cavities.

Table 17. Approximate middle trend effects of temperature on mechanical properties of clear wood at various moisture conditions.*

Property	Moisture condition	Relative change in mechanical property from 68 °F (20 °C)	
		At -58 °F (-50 °C)	At +122 °F (+50 °C)
	Percent (%)		
Modulus of elasticity parallel to grain	0 12 > FSP**	+11 +17 +50	-6 -7 —
Modulus of elasticity perpendicular to grain	6 12 ≥ 20	— — —	-20 -35 -38
Shear modulus	> FSP**	—	-25
Bending strength	≥ 4 11-15 18-20 > FSP**	+18 +35 +60 +110	-10 -20 -25 -25
Tensile strength parallel to grain	0-12	—	-4
Compressive strength parallel to grain	0 12-45	+20 +50	-10 -25
Shear strength parallel to grain	> FSP**	—	-25
Tensile strength perpendicular to grain	4-6 11-16 ≥ 18	— — —	-10 -20 -30
Compressive strength perpendicular to grain at proportional limit	0-6 ≥ 10	— —	-20 -35

* American Society of Civil Engineers Committee on Wood, Evaluation, Maintenance and Upgrading of Wood Structures, A Guide and Commentary, 1982.

** Moisture content higher than the fiber saturation point.

7.1.3.1 Extreme Temperatures

Considerable information is available on the mechanical and thermal properties of wood at temperature levels commonly encountered in structures, e.g., -50 °C to 50 °C, or –58 °F to 122 °F. The properties are observed to decrease with an increase in temperature and to increase with a decrease in temperature. Increasing the moisture content at the same time magnifies the response. Tensile strength parallel to the grain is the only property found to decrease with lower temperature. The work to maximum load increases until 32 °F (0 °C) is reached, but then decreases with a further drop in temperature.

Heating wood above given temperature levels causes a more precipitous decrease in some mechanical properties than in others. Tensile strength and modulus of elasticity (MOE) exhibit this behavior above 392 °F (200 °C) (Schaffer 1978). Other properties uniformly decrease with increased temperature. The thermal properties, with the exception of coefficient of thermal expansion, are functions of temperature.

In both hardwoods and softwoods, the parallel-to-the-grain thermal expansion coefficient ranges only from 1.7×10^{-6} to 2.5×10^{-6} per degree Farenheit (0.9×10^{-6} to 1.4×10^{-6} per degree Celsius). Across the grain, however, thermal expansion is greater than that along the grain, and it is also a function of wood specific gravity (Forest Products Laboratory 1987). For softwoods of structural quality, specific gravity can be assumed to be 0.5, and the resulting coefficients are between 26×10^{-6} to 35×10^{-6} degree Farenheit (14×10^{-6} per degree Celsius and 19.4×10^{-6} degree Celsius). Hence, across-the-grain thermal expansion is similar to that of steel or concrete.

For a softwood with dry specific gravity of 0.5 and moisture content of 12 percent the thermal conductivity is about 1.0.

7.1.3.2 Recoverable Effect

Theoretically, momentary exposure to intermediate heating and cooling regimes (-300 °F to 550 °F; -184 °C to 288 °C) should result in complete recovery of initial property levels. Short periods (minutes) of heating or cooling can have a practical effect, however. Because momentary cooling does not result in thermal degradation, it can be safely assumed that all mechanical properties completely recover after such exposure.

7.1.3.3 Time-Dependent Effects

A most commonly encountered design problem is the need to have a structural component continue to perform satisfactorily while subjected to heating or cooling for extended periods. When, however, wood is heated above room temperature (68 °F, 20 °C) for long periods of time, one must be on guard for permanent or irreversible changes that can occur. This is more likely to occur in steam-heated than in oven-heated type exposures, due to higher rates of degradation in hot moist environments.

It is known that tensile strength parallel to grain is well correlated to cellulose crystallinity in wood. Hence, until temperatures are generated that cause depolymerization of cellulose to occur, loss in tensile strength is not evident (Ifju 1964). Such loss in cellulose is not observed until temperatures in excess of 400 °F (205 °C) are

reached. This effect can be seen in the decrease in tensile strength above 400 °F (205 °C).

Compressive strength, unlike tensile strength, appears to increase with duration of heating at temperatures that cause significant thermal degradation to occur. When tested after 2 hours of heating, the compressive strength of oven-dry Douglas Fir increases as much as 10 percent when exposure temperatures exceed 199 °F (93 °C) (Schaffer 1970). Below this temperature level for this duration of heating, strength on return to room temperature is the same regardless of strength level at the elevated temperature. Information for longer periods of heating is unavailable.

The modulus of elasticity (parallel to grain) is relatively insensitive to durations of heating for temperatures below 284 °F (140 °C). However, short periods (2 h) above 284 °F (140 °C) do result in some reduction in the modulus of oven-dry wood (Schaffer 1970).

Although long-duration creep has been examined at temperatures of 77 °F (25 °C) and at several moisture contents, no similar long-term creep information is available at higher temperatures. Increasing the exposure temperature increases the rate of creep deformation (Arima 1973, Sawabe 1974, Schaffer 1970). As moisture content is increased as well, the creep rate is increased proportionately (Bach 1965). Hence, hot moist conditions are conducive to high creep deformation.

7.1.4 Moisture

It is common practice to dry (season) lumber less than about 3 in. in nominal thickness. The most common practice is to dry it in a kiln at elevated temperature to hasten the operation, while drying in the open air or in a shed may also be used if time is not a factor. Material from about 3 in. on up in thickness is commonly not dried because of the long time required and the difficulty of seasoning it without undesirable changes such as the development of deep seasoning checks. An approximate relationship of wood equilibrium moisture content, temperature, and relative humidity is shown by the curves in Figure 41, while the inset triangular diagram indicates the effect of wood moisture content on shrinkage. In general, as moisture content drops below the fiber saturation point — typically about 30 percent moisture content — wood properties begin to change.

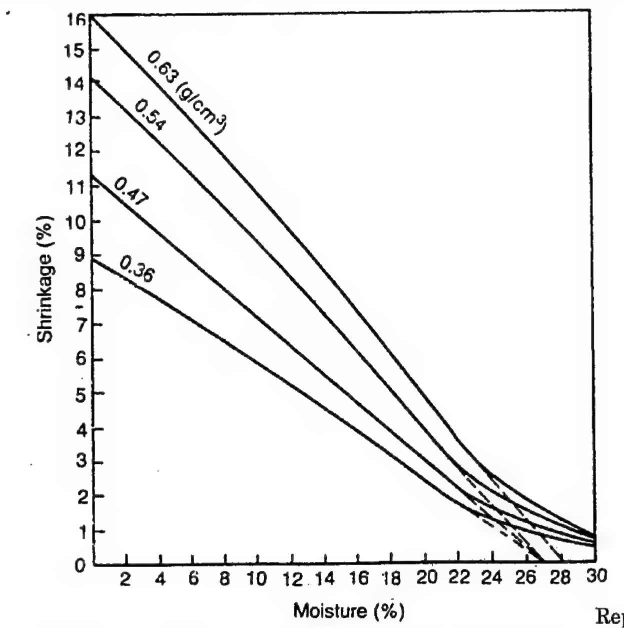


Figure 41. Relationships for moisture content, temperature, relative humidity, and shrinkage (Tsoumis 1991).

7.1.4.1 Dimensional Change

As moisture content decreases below the fiber saturation point, wood shrinks. Conversely, as moisture content rises to approach the fiber saturation point, wood swells. Wood changes dimension most in the direction parallel to the annual rings (tangentially), about half as much perpendicular to the annual rings (radially), and only slightly along the grain (longitudinally).

As a piece of wood dries, the moisture leaves it through its surfaces, and the remaining moisture migrates from the interior to the surface. In a piece having a relatively large cross section, the interior may retain large amounts of moisture and be above the fiber saturation point and thus stay constant in dimension, while the outer layers drop below the fiber saturation point and attempt to shrink. The inner core prevents keeps the drier outer shell from changing dimension, and tensile stresses develop perpendicular to the grain. When these stresses exceed the tensile strength of wood perpendicular to grain, failure results and an opening (termed a seasoning check) develops. As the moisture content continues to drop, the opening widens and deepens, and it is this phenomenon that explains why many timber structures built from large timbers have deep checks.

7.1.4.2 Fungus Attack

Decay and other fungi require a certain combination of circumstances in order to flourish. One such circumstance is the presence of moisture at or above the fiber saturation point. Thus, a wood member that has been installed at a high moisture content, or which has been subject to prolonged wetting, by leakage, spraying, rain, etc., may be subject to decay and thus to serious reduction in strength. Installation of dry lumber, design features that prevent wetting, and careful maintenance are essential to prevent decay.

At the incipient stage of degradation, no important differences are found between fungi or woods in most properties, but toughness is considerably affected. A toughness reduction of 30 – 50 percent may place before the weight of wood is reduced. Toughness may be almost nullified by a weight reduction of about 10%. Bending properties (modulus of rupture and elasticity) are less affected, and even smaller is the reduction of axial compression, transverse compression, and axial tension. Shear and hardness are little affected under the above-mentioned weight reduction. In general, mechanical properties are most sensitive to brown rot, and they should be assumed to be affected even if the wood is still hard and firm.

7.1.4.3 Insects

A number of insects require moisture to prosper. Some are found only where the moisture content of the wood is relatively high. Thus, for example, carpenter ants will be found only where the wood is saturated, commonly from leaks or entry of rainwater through end grain.

7.1.4.4 Mechanical Properties

As with physical properties, mechanical properties such as bending strength, tensile strength, compressive strength, and modulus of elasticity vary with moisture content below the fiber saturation point. Thus, a structural member that will be subject to high moisture content in service, such as an underwater application, will have less capacity to carry load than one which is kept continually dry, as in the interior of a building. Design stresses for wood are, therefore, keyed to service moisture content. That is, design stresses are commonly given for dry conditions of use or for wet conditions.

7.1.5 Chemicals

Wood offers many advantages as a construction material for use in corrosive environments. Knowledge of the chemical resistance and durability of wood is important to persons responsible for selecting construction materials for use under such conditions.

A species is usually chosen for chemical resistance on the basis of past experience and availability. In general, softwood species are more resistant than hardwood species, and heartwood is more resistant than sapwood. Experience has shown that lumber cut from the following species is suitable for water tanks: baldcypress, southern yellow pine, Douglas Fir, and redwood. Heartwood from the first three species is well suited for tanks where resistance to chemicals in appreciable concentrations is an important factor. These six species combine moderate-to-high resistance to water penetration with moderate-to-high resistance to decay. For structural members where exposure is usually limited to chemical fumes and dusts, the common structural species such as Douglas Fir, southern pines, true firs, and hemlock in the form of lumber and plywood provide adequate resistance to chemical attack.

7.1.5.1 Chemical Effects on Strength

Chemicals affect the strength of wood by two general types of action. One is an almost completely reversible effect involving swelling. The other type of action is nonreversible and involves permanent changes in the material as a result of a reaction between the chemical and the wood.

In the first type, chemicals such as alcohols, other polar solvents, and water will swell air-dry wood. The swelling causes no permanent effect on the strength properties, and removal of the swelling liquid returns the wood to nearly the original dimensions and strength. The loss in strength per unit area upon wetting wood in a polar solvent is proportionate to the amount of swelling.

The second type of action that causes permanent changes is exposure to acids, alkalis, and salts that attack the wood substance. For wood structures, chemical vapors and dusts are of concern. For instance acid vapors, and ammonia gas, and dust from stored salts, especially those that are hygroscopic, can affect structural members. The chemical attack reduces the strength properties in proportion to the amount of cross-sectional area attacked and the degree of attack.

The results of chemical actions are shown in loss of strength, and depend on wood species, type and concentration of chemical, duration of exposure, and temperature. Low concentrations of chemicals (for example, 2% solutions of hydrochloric acid, sodium hydroxide, and other acids and alkalis), acting at room temperature, have been shown to exercise little or no degrading effect on most of the species studied. Naturally, degradation increases with higher concentrations, and longer duration, and increasing temperatures. Studies with 10% concentrations, and temperatures of about 120 °F (50 °C), have shown that most species lost more than half (and some more than three-quarters) of their original strength.

Alkalis are more destructive; they reduce the modulus of elasticity, strength in bending, and transverse compression. In general, softwoods are more resistant than hardwoods, probably because they contain less hemicellulose. The effects of chemical solutions depend on the solvent. Nonswelling solvents have no important influence, but others (e.g., water) contribute to the reduction of strength due to swelling. Fire retardants in combination with kiln-drying may reduce bending strength (modulus of rupture) up to 10 percent. However, the modulus of elasticity was reported not to be substantially affected.

Aside from loss of strength, chemical exposure can cause changes in the color of wood. After air- or kiln-drying, the color of various woods becomes darker due to oxidation of cell contents. Discoloration in patches may also result from the chemical reaction of wood tannins with nails or other metallic or objects in the presence of moisture.

7.1.5.2 Acceptable Exposures for Long Service Life

Because even a small amount of chemical reaction usually has a great effect on wood strength properties, it is not possible to chemically analyze partially degraded wood to estimate the amount of strength loss. Usually, before a chemical change can be detected by routine chemical analysis, the wood has lost a substantial proportion of its strength.

Service conditions that are typically considered suitable for use of wood in contact with chemicals are as follow:

1. when the pH of the solution is between 2 and 11
2. when the temperature is lower than 122 °F (50 °C) most of the time
3. when there is no contact with oxidizing chemicals.

At the extremes of the pH range, the service life is shortened, especially at higher temperatures.

7.1.6 Weathering

Wood is very durable even under adverse conditions, but the durability depends upon specifics of the environment.

The importance of the various destructive agents on wood can best be considered by comparing two kinds of risk to wood structures. The most serious risk originating indoors is the intense heat of an accidental fire. Outdoors, the most significant risk is weathering — a complex combination of chemical, mechanical, and light energies.

Weathering should not be confused with decay, which results from organisms (fungi) acting in the presence of excess moisture and air for an extended period of time (DeGroot 1976). As discussed previously, under conditions suitable for the development of decay, wood can deteriorate rapidly, but the resulting phenomenon is very different than that observed for natural outdoor weathering.

7.1.6.1 The Weathering Process

In outdoor weathering of smooth wood, original surfaces become rough as grain loosens. Boards may cup or warp and pull away from fasteners. The roughened surfaces change color, gather dirt and mildew, and may become unsightly. The wood loses its surface coherence, splinters, fragments, and/or becomes friable.

7.1.6.2 Weathering Factors

The principal cause of weathering is frequent exposure of the wood surface to rapid changes in moisture content (Stamm 1965, Stamm and Loughborough 1942). Rain or dew falling upon unprotected wood is quickly absorbed by capillary action on the surface layer of the wood followed by adsorption within wood cell walls. Water vapor is taken up directly by adsorption under increased relative humidities. Adsorbed water has been shown to virtually add its volume to that of the cell walls, resulting in swelling (Stamm 1963, Stamm 1964). Stresses are set up in the wood as it swells and shrinks due to moisture gradients between the surface and the interior (Forest Products Laboratory 1987). These induced stresses are greater where the moisture gradient is steeper, and they are usually concentrated near the surface of the wood. When unbalanced, they may result in warping, cupping, and face checking. Grain raising results from differential swelling and shrinking of summerwood and springwood.

The photochemical degradation of wood or wood-related materials has been reviewed in several publications (Coupe and Watson 1967, Kalnins 1966, Sell 1975). It was recognized quite early that the initial color change of wood exposed to sunlight was a yellowing or browning (Cal. Red. Assoc. 1962, Feist 1980). The graying of wood occurs after browning, and was at one time thought to be related to iron salts. Sunlight, particularly the ultraviolet (UV) end of the spectrum, degrades the organic materials in wood.

It is important to note here that the two most important elements of weathering — light irradiation and water — tend to operate at different times. Exposed wood can be irradiated after having been wet by rain or when surface moisture content is high from overnight high humidity or from dew. Time of wetness, therefore, is an important parameter in relating climatic conditions to exterior degradation. The action of the combined elements can follow different degradation paths, with irradiation accelerating the effect of water or the converse.

7.1.6.3 Property Changes

In addition to chemical and color changes caused by outdoor weathering, mechanical degradation can also occur. Decomposition of a wood surface due to the combined action of light and water causes surface darkening and leads to formation of both macroscopic and microscopic cracks or checks. There is a loss of strength in cell wall bonds near the wood surface. As the weathering process continues, rain water washes out degraded portions, and further erosion takes place. Because of different types of wood tissue on the surface, erosion and checking differ in intensity and the wood surface becomes increasingly uneven (Figure 42 [Forest Products Laboratory 1987]).

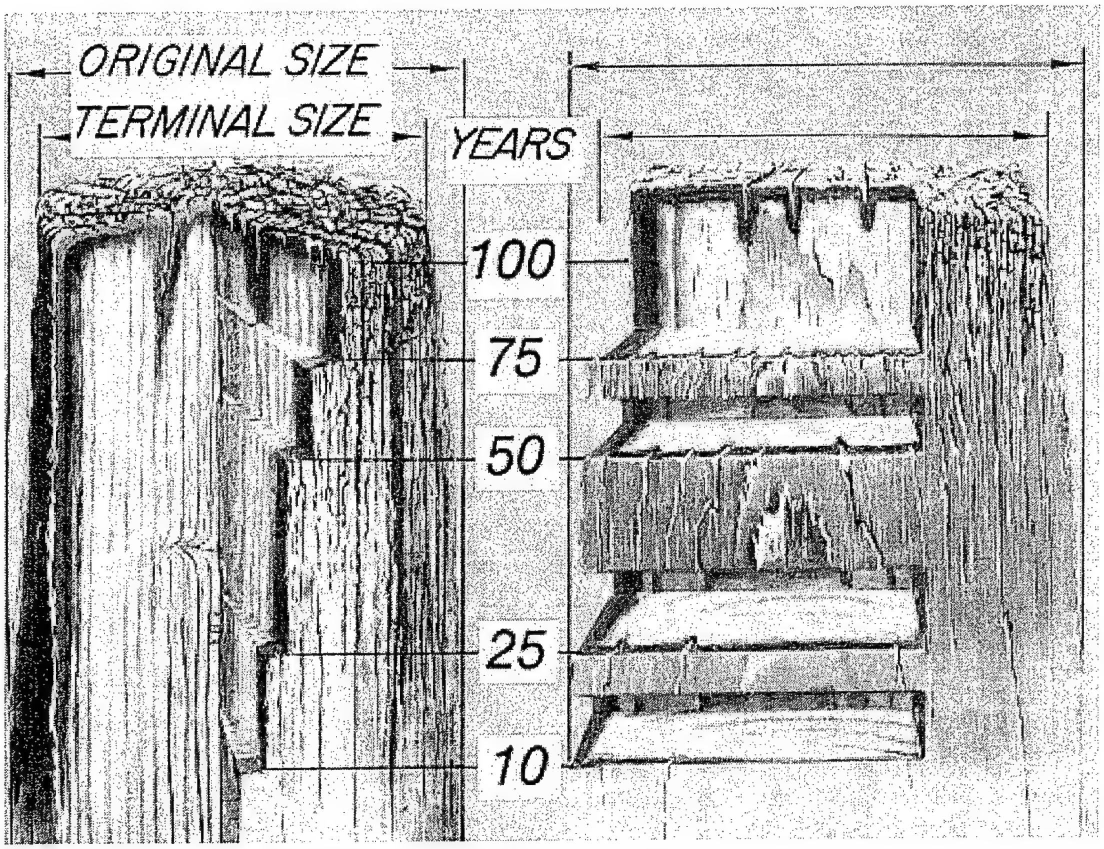


Figure 42. Weathering process of round and square timbers.

7.1.7 Checks, Shakes, and Splits

Checks and shakes, which are defined as separations perpendicular to the grain, can reduce the stiffness and load-carrying capacity of wood. Usually, checks result from drying stresses while shakes are usually present in the standing tree or appear a short time after processing begins. Figure 43 presents both types of separations.

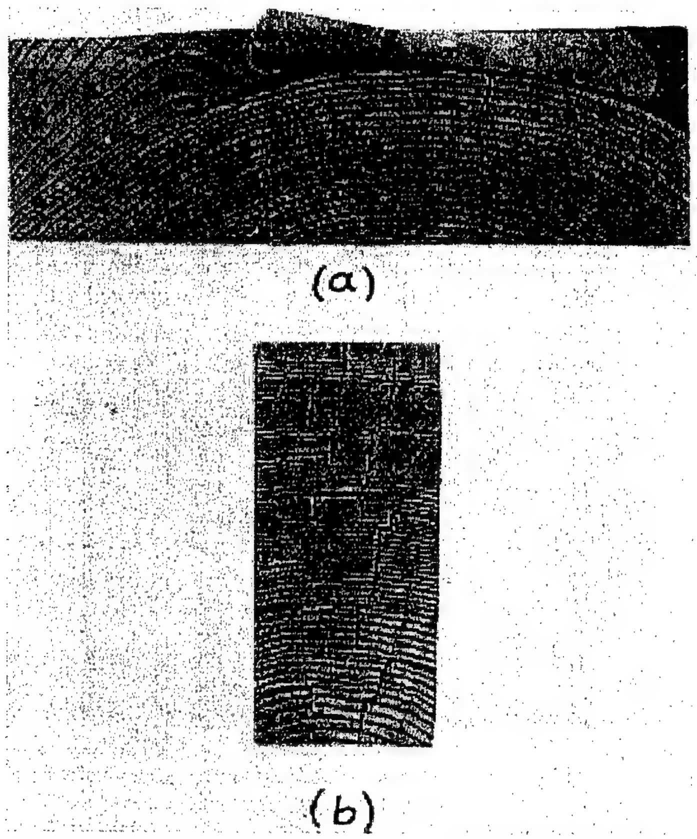


Figure 43. Discontinuities in wood: shake (a) and check (b).

The tensile strength of wood parallel to grain is virtually unaffected by the presence of either type of separation. However, when loaded in compression, a severely checked structural member tends to react as several columns with much higher slenderness ratios than those of the uncracked column. As a result, the ultimate compression stress is lowered and the load-carrying capacity of the column is greatly reduced.

The location and orientation of the plane of separation is critical for assessing the effect of checks and shakes on the load-carrying capacity of beams. The effect depends on the proximity and closeness of alignment of the separation to the neutral plane. When a complete separation occurs at the neutral plane, the resistance to shear stress and the moment of inertia are reduced markedly, thereby affecting bending strength. The moment of inertia about the neutral plane of the beam shown in Figure 44 (a) is:

$$I = \frac{bh^3}{12}$$

If the separation is present at the neutral plane (Figure 44 (b)), the effective moment of inertia, $I\square$, must be calculated as follows:

$$I' = 2\frac{b(h/2)^3}{12} = \frac{bh^3}{48}$$

Consequently, the moment of inertia is reduced to 25 percent of its original value. Since the deflection of a beam is inversely proportional to the moment of inertia, load-carrying capacity is reduced accordingly. A separation which begins at one face and penetrates partly through the beam (Figure 44 (c)) is a much more common defect than splitting. As a first approximation, a beam with partial separation is sometimes analyzed as a set of three beams; the checked portion as two beams and the unchecked portion as a single beam. However, although this approximation is sometimes used, there is insufficient experimental evidence to prove it. The effects of a separation on the bending and shear stresses are based on similar considerations using the changes in section modulus and area moment, respectively.

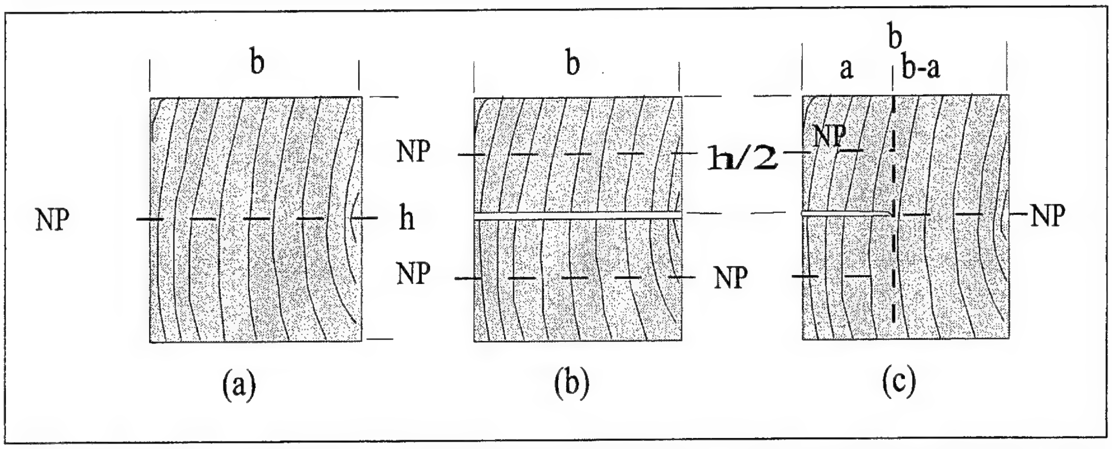


Figure 44. Effect of separation on cross-sectional properties of beam: (a) solid section, (b) split at neutral plane, (c) check at neutral plane.

In addition to the cross-sectional considerations, location of the separation along the length of a beam is also critical. Since maximum moment for simple beams is usually located near mid-span, while checks are concentrated near the ends of a beam, the effect of a separation on the bending stress and deflection is usually minimal. Furthermore, even if the separation is located at the end of a beam, it will seldom be at the neutral plane and is unlikely to be coplanar with the plane of maximum stress.

7.2 Predictive Service Life Testing of Components

The service life of structural components is normally defined as the period of time after installation during which essential properties meet or exceed the minimum acceptable values. Components and materials have finite service lives because they

gradually undergo chemical, physical, or mechanical changes that degrade them and reduce their ability to perform as required. The term *aging* is frequently used to describe such changes in properties with time.

The approximate service lives of components and materials that have been used extensively in structures are usually known from experience. However, for new types of components and materials, and for conventional components and materials to be used in new applications, this experience is not available and the service life is seldom known with the same confidence. When service life data are unavailable or inadequate, tests must be performed to measure or predict service life.

7.2.1 Service Life Tests

A service life test includes a property measurement test and an aging test. Properties that are important to performance are measured both before and after aging to determine the rate at which properties change. A known rate of degradation permits the extrapolation of short-term data to predict long-term performance, assuming the degradation follows a known function with time.

7.2.1.1 Property Measurement Tests

Property measurement tests provide for the measurement of one or more properties of a component or material. Table 18 lists a number of important properties of wood and ASTM test methods for measuring those properties. Properties such as those listed in Table 18 may be useful indicators in performing service life tests of wood and wood products.

Table 18. Some typical ASTM property measurement tests for wood.

Property	ASTM Test Designation
Static properties of structural timber	D198
Moisture absorption of wood	D3502
Specific gravity of wood and wood-base materials	D2395
Moisture content of wood	D2016
Water solubility of wood	D1110
Alcohol-benzene solubility of wood	D1107
Strength values of clear wood	D2555
Tests for small, clear timber specimens	D143

7.2.1.2 Aging Tests

Aging tests provide one or more means of exposing components to factors that may induce changes in their properties. The changes induced in properties usually re-

duce the ability of the component to perform its intended functions. Factors that are typically included in aging tests to induce changes in component properties are termed *degradation factors*. Figure 45 presents these factors, including weathering, biological, stress, incompatibility, and use factors. Table 19, which lists some ASTM aging tests for wood, illustrate the types of standard aging tests that are currently available.

Table 19. Some degradation factors affecting wood and ASTM aging tests for those factors.

Degradation Factors	ASTM Test Designation
Weathering	
Solar radiation	—
Temperature	—
Water	D3502, D3503
Biological	
Fungi	D2017
Termites	D3345

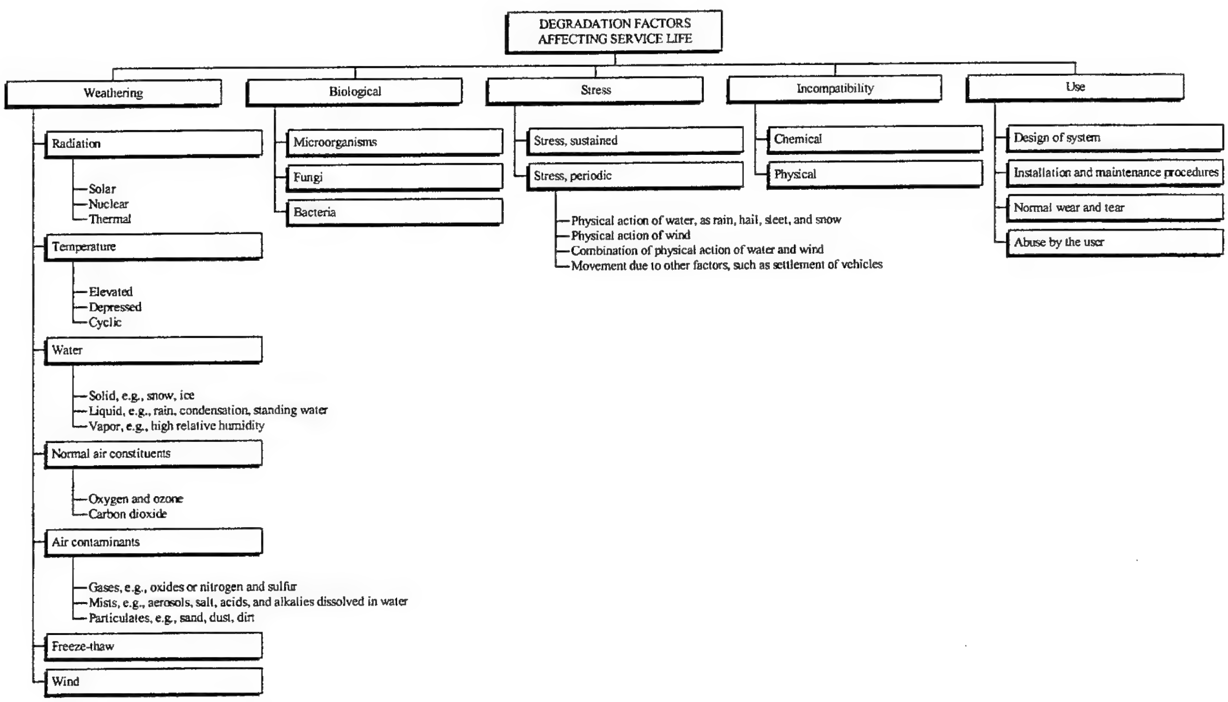


Figure 45. Degradation factors affecting the service life of building components and materials.

The advantage of aging tests involving in-service exposure in structures is that they are real-life tests, and the results thus correlate with in-service performance. Disadvantages are the length of time often required to obtain results and the high cost of conducting the tests, including the cost of supplying, installing, and maintaining complete structures. Another possible cost may occur in the form of manufacturer

revenue losses arising from delays in the marketing of components while awaiting long-term test results.

The advantage of conducting exposure tests at test sites (as opposed to the working facility) is that the tests can be performed rapidly under controlled conditions while reasonably simulating real-world exposures. They have the same disadvantages as in-service exposure tests if complete structures are tested. The time to obtain results is one disadvantage. Another is that the test components may not undergo the same stresses as in the complete structure.

Short-term (i.e., accelerated) aging tests are advantageous in terms of yielding timely results. Another advantage is that the effect of single or specific groups of degradation factors can be studied under controlled conditions. The primary disadvantage is that the results of accelerated tests often have uncertain correlation to long-term in-service performance.

7.2.2 ASTM Systematic Approach

American Society for Testing and Materials (ASTM) recommended practice ASTM E632-77 based on NIST research that describes a systematic approach, applicable to all components and materials comprising a building system. The recommended practice, as outlined in Figure 46, is divided into four parts: (1) problem definition, (2) pre-testing, (3) testing, and (4) interpretation and reporting of data. This systematic approach provides guidelines for evaluating existing predictive service life tests and for developing new, more reliable tests as they are needed. This approach should also lead to improved tests by requiring consideration of all important factors affecting service life and identifying data needed to develop more sophisticated tests. Furthermore, use of the guidelines will help to provide a clear context for service life predictions by requiring those who develop predictions to document their assumptions and their assessments of uncertainties in the test results and predictions.

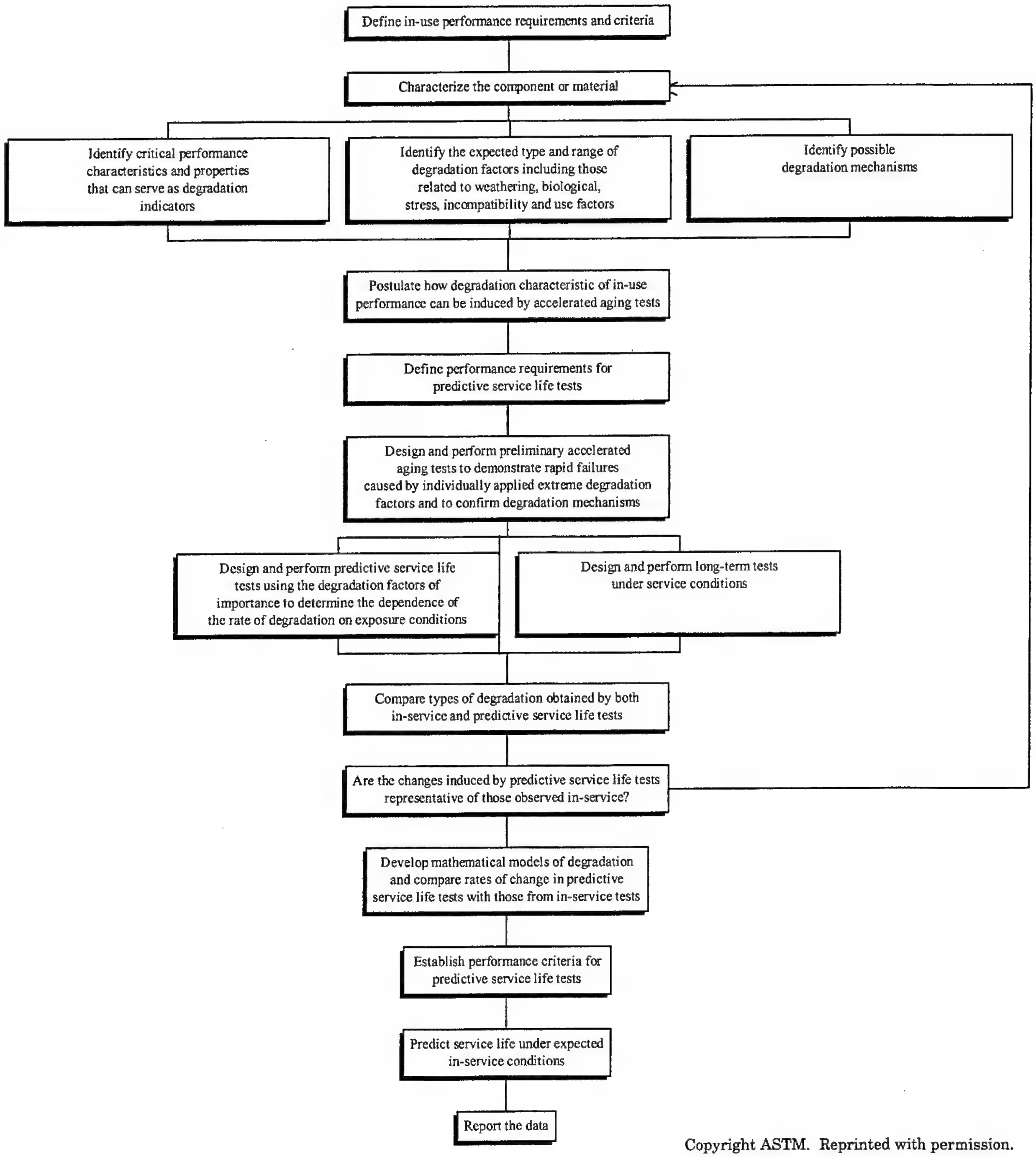


Figure 46. Outline of systematic approach for developing predictive service life tests.

8 Summary

This report has presented technical information and procedures that are essential for inspecting wood structures and understanding the results. The text addresses wood species characteristics, structural properties, building code considerations, and the effects of environmental factors, including organisms, microorganisms, and nonliving substances such as corrosive chemicals. Inspection procedures that were covered include guidance on visual identification of wood types, grades, and mechanical stressors; creation of a consolidated wood structure inspection checklist and flow chart; application of qualitative nondestructive field and laboratory tests to determine the basic mechanical properties of the inspected wood materials; and use of qualitative visual inspection procedures that attempt to minimize subjective variations in inspector judgment.

The text describes general types and grades of wood used in load-bearing structural elements. Guidelines and photographs are included to help inspectors identify wood types and grades through visual, field, and laboratory tests. Also included is a comprehensive checklist of all commercially used wood structural members. Published structural properties, such as modulus of elasticity, density, and moisture conditions, are summarized and presented. Also, the durability of each common construction grade of wood is related to the environmental factors that influence its performance. The text includes a thorough summary of the effects of aging, sustained temperature extremes, humidity, exposure to chemicals, organisms, and other environmental factors that contribute to structural degradation. In addition, field and laboratory testing to identify the grades of wood and to determine their mechanical properties are outlined.

Guidelines are presented to help inspectors compare the existing condition of a structure with its original design and determine the margin of safety in terms of current code requirements. A rating system based on current codes is presented to evaluate and assess structures designed and built using older codes. Serviceability of wood grades in terms of their required properties is also discussed, and strength-reducing factors are addressed. However, it must be reiterated that this document is intended to support field inspection of wood structures, but *not* to serve as a substitute for structural engineering expertise. If the findings of a wood condition inspection raise concerns or questions about structural integrity, then it is essential to seek immediate assistance from a trained and qualified structural engineer.

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Glossary

Advanced (or Typical) Decay: The later stage of decay in which the destruction is readily recognized because the wood has become punky, soft and spongy, stringy, ringshaked, pined, or crumbly. Discoloration or bleaching of the rotted wood is often apparent.

Air-Dried: Wood dried by exposure to the atmosphere without an artificial heat source.

Allowable Stress: The maximum allowable material stress used for the design of timber members. Allowable stress equals the tabulated stress adjusted by all applicable modification factors.

American Softwood Lumber Standard: A Voluntary Product Standard (PS 20-99) published by the U.S. Department of Commerce in consultation with the American Lumber Standard Committee, a not-for-profit industry/consumer advisory board appointed by the Department of Commerce. PS 20-99 comprises recognized classifications, nomenclature, basic grades, sizes, description, measurements, tally, shipping provisions, grademarking, and inspection of softwood lumber. The primary purpose of these standards is to serve as a guide in the preparation or revision of the grading rules of the various lumber manufacturer associations.

Anisotropic: The converse of "isotropic"; not having the same properties in all directions. In general, fibrous materials such as wood are anisotropic.

Annual Growth Ring: The layer of wood growth on a tree during a single growing season. In the temperate zone the annual growth rings of many species, e.g., pines, are readily distinguished because of differences in the cells formed during the early and late parts of the season. Annual growth rings are easily recognized.

Beam: A structural member supporting a transversely applied load.

Blue Stain: A bluish or grayish discoloration of the sapwood caused by the growth of certain dark-colored fungi on the surface and in the interior of the wood; made possible by the same conditions that favor the growth of other fungi.

Boards: Lumber that is nominally less than 2 in. thick and 2 or more in. wide. Boards less than 6 in. wide are sometimes called strips.

Brown Rot: Any wood decay in which the attack concentrates on the cellulose rather than on the lignin, producing a light to dark brown friable residue. An advanced stage where the wood splits along rectangular planes, in shrinking, is termed "cubical rot".

Cambium: A thin layer of tissue between the bark and wood that repeatedly subdivides to form both new wood and new bark cells.

Cellulose: The carbohydrate that is the principal constituent of wood and forms the framework of the wood cells.

Check: A lengthwise separation of the wood that usually extends across the rings of annual growth and commonly results from stress set up in wood during seasoning.

Chemical Brown Stain: A chemical discoloration of wood, which sometimes occurs during the air drying or kiln drying of several species, apparently caused by the concentration and modification of extractives.

Chord: In a truss, the upper and lower longitudinal members, extending the full length and carrying the tensile and compressive forces that form the internal resisting moment.

Close-Grained Wood: Wood with narrow, inconspicuous rings. The term is sometimes used to designate wood having small and closely spaced pores, but in this context the term "fine-textured" is more often used.

Coarse-Grained Wood: Wood with wide, conspicuous annual rings in which there is considerable difference between springwood and summerwood. The term is sometimes used to designate wood with large pores, such as oak, ash, chestnut, and walnut, but in this sense the term "coarse-textured" is more often used.

Column: A general term applying to a member resisting compressive stress and having, in general, a considerable length in comparison with its transverse dimensions.

Compression Failure: Deformation of the wood fibers resulting from excessive compression along the grain either in direct end compression or in bending. In sur-

faced lumber, compression failures may appear as fine wrinkles across the face of the piece.

Conditioning (pre and post): The exposure of a material to the influence of a prescribed atmosphere for a stipulated period of time or until a stipulated relation is reached between material and atmosphere.

Connector, Timber: Metal rings, plates, or grids which are embedded in the wood of adjacent members, as at the bolted points of a truss, to increase the strength of the joint.

Cross Section: The surface obtained when cutting a log perpendicular to its long axis or a piece of wood perpendicular to the longitudinal direction.

Cross-Grained Wood: Wood in which the fibers deviate from a line parallel to the sides of the piece. Cross grain may be either diagonal or spiral grain, or a combination of the two.

Dead Load: The static load imposed by the weight of the materials that make up the structure.

Decay: The decomposition of wood substance by fungi.

Delamination: The separation of layers in laminated wood or plywood due to failure of the adhesive, either within the adhesive itself or at the interface between the adhesive and the adherent.

Density: As usually applied to wood of normal cellular form, density is the mass of wood substance enclosed within the boundary surfaces of a wood-plus-voids complex having unit volume. It is variously expressed as pounds per cubic foot, kilograms per cubic meter, or grams per cubic centimeter at a specified moisture content.

Design Load: The loading comprising magnitudes and distributions of all loads used in the determination of the stresses, stress distributions, and ultimately the cross-sectional areas and compositions of the various portions of a structure.

Diagonal-Grained Wood: Wood in which the annual rings are at an angle with the axis of a piece as a result of sawing at an angle with the bark of the tree or log. A form of cross-grain.

Diaphragm: Blocking between two main longitudinal beams, consisting of solid lumber or glued-laminated timber.

Dimension Lumber: Lumber with a nominal thickness of from 2 in. up to but not including 5 in., and a nominal width of 2 in. or more.

Dressed Lumber: The dimensions of lumber after being surfaced with a planing machine. The dressed size is usually 0.5 to 0.75 in. less than the nominal or rough size.

Dry: Wood having a relatively low moisture content, by definition 19 percent for sawn lumber and 16 percent for glued laminated timber.

Dry Rot: A term loosely applied to any dry, crumbly rot, but especially to that which, when in an advanced stage, permits the wood to be crushed easily to a dry powder. The term is actually a misnomer for any decay since all fungi require considerable moisture for growth.

Durability: A general term for permanence or resistance to deterioration. Frequently used to refer to the degree of resistance a species of wood has to attack by wood-destroying fungi under conditions that favor such attack.

Duration-of-Load Factor: A factor expressing the dependence of wood strength on the duration of the loading.

Earlywood: The portion of the annual growth ring that is formed during the early part of the growing season. It is usually less dense and mechanically weaker than latewood.

Edge-Grained Lumber: Lumber that has been sawed so that the wide surfaces extend approximately at right angles to the annual growth rings. Lumber is considered edge grained when the rings form an angle of 45 - 90 degrees with the wide surface of the piece.

Encased Knot: A knot whose rings of annual growth are not intergrown with those of the surrounding wood.

End-Grained Wood: The grain as seen on a cut made at a right angle to the direction of the fibers.

Factor of Safety: A factor or allowance predicated by common engineering practice upon the failure stress or stresses assumed to exist in a structure or a member or part thereof. Its purpose is to provide a margin in the strength, rigidity, deformation, and endurance of a structure or its component parts in order to compensate for irregularities existing in structural materials.

Factory and Shop Lumber: Lumber intended to be cut up for use in further manufacture. It is graded on the basis of the percentage of the area that will produce a limited number of cuttings of a specified minimum size and quality.

Fatigue: The decrease in member strength when subjected to cyclical loading (as applied to static loading).

Fiber Saturation Point: The stage in the drying or wetting of wood at which the cell walls are saturated and the cell cavities free from water. The term applies to an individual cell or group of cells, not to whole boards. It is usually taken as approximately 30 percent moisture content, based on oven-dry weight.

Figure: The pattern produced in a wood surface by annual growth rings, rays, knots, deviations from regular grain such as interlocked and wavy grain, and irregular coloration.

Fire Retardant: A chemical or preparation of chemicals used to reduce flammability or to retard spread of a fire over the surface.

Flat-Grained Wood: Lumber that has been sawed parallel to the pith and approximately tangent to the growth rings. Lumber is considered flat grained when the annual growth rings make an angle of less than 45 degrees with the surface of the piece.

Floor Beam: A beam located transverse to the bridge alignment that supports the deck or other components of a floor system.

Frass: Insect droppings.

Girder: A large or principal beam used to support concentrated loads at isolated points along its length.

Glued-Laminated Timber (Glulam): An engineered, stress-rated product of a timber-laminating plant comprising assemblies of specially selected and prepared wood laminations securely bonded together with adhesives.

Grade: The designation of the quality of a log or a milled piece of wood.

Grade Stamp: Identification of lumber with symbols or lettering to certify its quality or grade.

Grain: The direction, size, arrangement, appearance, or quality of the fibers in wood or lumber. To have a specific meaning the term must be qualified.

Green: Freshly sawed or undried wood. Wood that has become completely wet after immersion in water would not be considered green, but may be said to be in the green condition.

Hardness: A property of wood that enables it to resist indentation.

Hardwoods: Generally one of the botanical groups of trees that have broad leaves in contrast to the conifers or softwoods. The term implies no reference to the actual hardness of the wood.

Heartwood: The wood extending from the pith to the sapwood, the cells of which no longer participate in the life processes of the tree. Heartwood may contain phenolic compounds, gums, resins, and other materials that usually make it darker and more decay-resistant than sapwood.

Impact: A dynamic increment of stress equivalent in magnitude to the difference between the stresses produced by a static load and those produced by the same loads applied dynamically.

Incipient Decay: The early stage of decay that has not proceeded far enough to soften or otherwise perceptibly impair the hardness of the wood. It is usually accompanied by a slight discoloration or bleaching of the wood.

Increment Borer: An augerlike instrument with a hollow bit and an extractor, used to extract thin radial cylinders of wood from trees to determine age and growth rate. Also used in wood preservation to determine the depth of penetration of a preservative.

Intergrown Knot: A knot whose rings of annual growth are completely intergrown with those of the surrounding wood.

Interlocked-Grained Wood: Grain in which the fibers put on for several years may slope in a right-handed direction, and then for a number of years the slope re-

verses to a left-handed direction, and later changes back to a right-handed pitch, and so on. Such wood is exceedingly difficult to split radially, though tangentially it may split fairly easily.

Isotropic: The quality of having properties that are independent of the direction in which they are measured; properties are equal in all directions. The converse of "anisotropic."

Joist: One of a series of parallel beams used to support floor and ceiling loads and supported in turn by larger beams, girders, or bearing walls.

Juvenile Wood: The wood formed adjacent to the pith.

Knot: That portion of a branch or limb that has been surrounded by subsequent growth of the stem. The shape of the knot as it appears on a cut surface depends on the angle of the cut relative to the long axis of the knot.

Laminated Wood: An assembly made by bonding layers of veneer or lumber with an adhesive so that the grain of all laminations is essentially parallel. (Compare with "plywood.")

Latewood: The portion of the annual growth ring that is formed late in the growing season, after the earlywood formation has ceased.

Live load: A dynamic load that is applied to a structure suddenly or that is accompanied by vibration, oscillation, or other physical condition affecting its intensity.

Loose Knot: A knot that is not held firmly in place by growth or position and that cannot be relied upon to remain in place.

Lumber: The product of the saw and planing mill not further manufactured than by sawing, resawing, passing lengthwise through a standard planing machine, crosscutting to length, and matching.

Machine Stress Rated (MSR) Lumber: A grade of structural lumber determined by measuring the stiffness of each piece by a grading machine.

Marine Borers: Marine organisms that attack wood in the submerged portions of structures located in salt or brackish waters.

Matched Lumber: Lumber that is edge-dressed and shaped to make a close tongued-and-grooved joint at the edges or ends when laid edge to edge or end to end.

Modification Factor: A multiplicative factor applied to tabulated stress for lumber and glulam to compensate for various design and/or use conditions.

Modified Wood: Wood processed by chemical treatment, compression, or other means (with or without heat) to impart properties significantly different from those of the original wood.

Modulus of Rupture (MOR): Maximum stress at the extreme fiber in bending, calculated from the maximum bending moment on the basis of an assumed stress distribution. In clear wood, the value of the modulus of rupture is intermediate between the tensile and compressive strengths.

Modulus of Elasticity (MOE): Also known as Young's Modulus, this is a material property that equals elastic stress in a material divided by corresponding elastic strain.

Moisture Content: The amount of water contained in the wood, usually expressed as a percentage of the weight of the oven-dry wood.

Moisture Meter: An electrical instrument used to indicate the moisture content of wood.

Nominal size: The size by which timber or lumber is known and sold in the market, often differing from the wood's actual dimensions.

Neutral Plane: In a material subject to bending, the plane in which bending stresses and strains are zero.

Nondestructive Evaluation: The measurement of mechanical properties using procedures that do not destroy the tested material.

Old Growth: Timber in or from a mature, naturally established forest. When the trees have grown during most if not all of their individual lives in active competition for sunlight and moisture, this timber is usually straight and relatively free of knots.

Open-Grained Wood: Common classification for woods with large pores, such as oak, ash, chestnut, and walnut. Also known as "coarse-textured."

Orthotropic: Having unique and independent properties in three mutually orthogonal (perpendicular) planes of symmetry; a special case of anisotropy.

Oven-Dry Wood: Wood dried to a relatively constant weight in a ventilated oven at 216 – 221 °F (102 – 105 °C).

Overload: In general, any load that is in excess of the design load.

Pile: A long, heavy timber, round or square, that is driven deep into the ground to provide a secure foundation for structures built on soft, wet, or submerged sites; e.g., landing stages, bridge abutments.

Pitch: An accumulation of resinous material in wood.

Pith: The small, soft core occurring near the center of a tree trunk, branch, twig, or log.

Plainsawed Lumber: Another term for flat-grained lumber.

Plank: A broad board, usually more than 1 in. thick, laid with its wide dimension horizontal and used as a bearing surface.

Plywood: A glued wood panel made up of relatively thin layers of veneer with the grain of adjacent layers at right angles, or of veneer in combination with a core of lumber or of reconstituted wood. (Compare with "Laminated Wood.")

Pocket Rot: Advanced decay in wood that appears in the form of a hole or pocket, usually surrounded by apparently sound wood.

Preservative: Any substance that, for a reasonable length of time, is effective in preventing the development and action of wood-rotting fungi, borers of various kinds, and harmful insects.

Pressure Process: Any process of treating wood in a closed container whereby a preservative or fire retardant is forced into the wood under pressures greater than atmospheric pressure. The American Wood Preservers' Association usually denotes pressure as greater than 50 psi.

Quartersawed Lumber: Another term for edge-grained lumber; often called "quartersawn."

Radial: Coincident with a radius from the axis of the tree or log to the circumference. A radial section is a lengthwise section in a plane that passes through the centerline of the tree trunk.

Rays, Wood: Strips of cells extending radially within a tree, varying in height from a few cells in some species to 4 or more inches in oak. Rays serve primarily to store food and transport it horizontally in the tree. On quartersawed oak, the rays form a conspicuous figure, sometimes referred to as flecks.

Relative Humidity: Ratio of the amount of water vapor present in the air to that which the air would hold at saturation at the same temperature. It is usually considered on the basis of the weight of the vapor but, for accuracy, should be considered on the basis of vapor pressures.

Resin: Inflammable, water-soluble vegetable substances secreted by various plants or trees, especially many coniferous species. The term is also applied to synthetic organic products chemically related to the natural resins.

Resin Ducts: Intercellular passages that contain and transmit resinous materials. On a cut surface, they are usually inconspicuous. They may extend vertically parallel to the axis of the tree, or at right angles to the axis and parallel to the rays.

Rheology: The study of the deformation and flow of matter.

Ring-Porous Woods: A group of hardwoods in which the pores are comparatively large at the beginning of each annual ring and decrease in size more or less abruptly toward the outer portion of the ring, thus forming a distinct inner zone of pores known as the earlywood. The outer zone, with smaller pores, is known as the latewood.

Rough Lumber: Lumber that has not been dressed (surfaced) but that has been sawed, edged, and trimmed.

Sapwood: The wood of pale color near the outside of a log. Under most conditions the sapwood is more susceptible to decay than heartwood.

Seasoning: Removing moisture from green wood to improve its serviceability.

Second Growth: Timber that has grown after the removal, whether by cutting, fire, wind, or other agency, of all or a large part of the previous stand.

Shake: A separation along the grain, the greater part of which occurs between the rings of annual growth. Usually considered to have occurred in the standing tree or during felling.

Sheathing: The structural covering — usually of boards, building fiberboards, or plywood — placed over exterior studding or rafters of a structure.

Side-Grained Wood: Another term for flat-grained lumber.

Slash-Grained Wood: Another term for flat-grained lumber.

Soft Rot: A special type of decay developing under very wet conditions in the outer wood layers, caused by cellulose-destroying microfungi.

Softwoods: In general, one of the botanical groups of trees that in most cases have needlelike or scalelike leaves; the conifers, also the wood produced by such trees. The term implies no reference to the actual hardness of the wood.

Specific Gravity: As applied to wood, the ratio of the oven-dry weight of a sample to the weight of a volume of water equal to the volume of the sample at a specified moisture content (green, air-dry, or oven-dry).

Spiral-Grained Wood: Wood in which the fibers take a spiral course about the tree trunk instead of the normal vertical course. The spiral may extend in a right-handed or left-handed direction around the tree trunk. Spiral grain is a form of cross grain.

Split: A separation of the wood from the tearing apart of the wood cells.

Stain: A discoloration in wood that may be caused by such diverse agencies as microorganisms, metal, or chemicals. The term also applies to materials used to apply aesthetic color to wood.

Stiffness: Resistance to deformation by loads that cause bending stress.

Straight-Grained Wood: Wood in which the fibers run parallel to the axis of a piece.

Strain: A unitless value given by the elongation of a material divided by its original length.

Strength ratio: The hypothetical ratio of the actual strength of a structural member to that which it would have if it contained no strength-reducing characteristics (knots, cross-grain, shake, and so forth).

Strength: The ability of a member to sustain stress without failure.

Stress grades: Lumber grades with assigned working stress and modulus of elasticity values in accordance with accepted basic principles of strength grading.

Stress: The intensity of forces distributed over a given section measured as force per unit area.

Stringer: A timber or other support for cross members in floors or ceilings.

Structural Lumber: Lumber that is graded for use where allowable properties are required. The grading of structural lumber is based on the strength or stiffness of the piece as related to anticipated uses.

Structural Timber: A piece of wood of relatively large size, the strength or stiffness of which is the controlling element in its selection and use. Examples of structural timbers are trestle timbers (stringers, caps, posts, sills, bracing, bridge ties, guardrails); framing for building (posts, sills, girders); and crossarms for poles.

Summerwood: See "Latewood".

Tangential: The direction in wood coincident with a tangent at the circumference of a tree or the annual growth rings. A tangential section is a longitudinal section through a tree perpendicular to a radius.

Texture: A term often used interchangeably with grain. Sometimes used to combine the concepts of density and degree of contrast between earlywood and latewood. In this report, texture refers to the finer structure of the wood (see "Grain") rather than the annual rings.

Timbers: Lumber that is nominally 5 in. or more in its smaller dimension.

Toughness: A characteristic of wood that permits the material to absorb a relatively large amount of energy, to withstand repeated shocks, and to undergo considerable deformation before breaking.

Tracheid: The elongated cells that constitute the greater part of the structure of the softwoods (frequently referred to as fibers). Also present in some hardwoods.

Transverse: Directions in wood at right angles to the wood fibers. Includes radial and tangential directions. A transverse section is a section through a tree or timber at right angles to the pith.

Truss: An assembly of members such as beams, bars, rods, and the like combined to form a rigid framework; members are interconnected to form triangles.

Unseasoned: Wood that is freshly sawed from green logs; specifically, wood not dried to 19 percent or lower moisture content.

Vertical-Grained Lumber: Another term for edge-grained lumber.

Vessels: Wood cells of comparatively large diameter that have open ends and are set one above the other to form continuous tubes. The openings of the vessels on the surface of a piece of wood are usually referred to as pores.

Virgin Growth: The growth of mature trees in an original forest.

Visual Stress Grade Lumber: A grade of structural lumber determined by estimating the influence of strength-reducing characteristics by visual examination of the surfaces.

Weathering: The mechanical or chemical disintegration and discoloration of the surface of wood caused by exposure to light, the action of dust and sand carried by winds, and the alternate shrinking and swelling of the surface fibers with the continual variation in moisture content brought by changes in the weather. Weathering does not include decay.

Wetting: The process in which a liquid spontaneously adheres to and spreads on a solid surface.

White Rot: In wood, any decay or rot attacking both the cellulose and the lignin, producing a generally whitish residue that may be spongy or stringy rot, or may occur as pocket rot.

Yard Lumber: A little-used term for lumber of all sizes and patterns that is intended for general building purposes having no design property requirements.

Appendix A: Engineering Information for Wood Structure Inspectors

This appendix includes supplemental technical information for wood inspectors about select softwood species. This information was extracted from the Department of Agriculture publication entitled *Atlas of United States Trees: Volume 1: Conifers and Important Hardwoods* (Miscellaneous Publication No. 1146, Elbert L. Little, Jr., Division of Timber Management Research, Forest Service, Washington, DC., March 1971. Table A1 lists the geographical range where each species grows in the continental United States.

Table A1. Geographic location of the softwoods used in construction.

Softwood	Location
Southern Cypress	Alabama, Arkansas, Delaware, Florida, Georgia, Illinois, Indiana, Kentucky, Louisiana, Maryland, Mississippi, Missouri, North Carolina, Oklahoma, South Carolina, Tennessee, Texas, Virginia
Douglas Fir	Arizona, California, Colorado, Idaho, Montana, Nevada, New Mexico, Oregon, Texas, Utah, Washington, Wyoming
True fir (Eastern Species)	Connecticut, Iowa, Maine, Massachusetts, Michigan, Minnesota, New Hampshire, New York, Pennsylvania, Vermont, Virginia, West Virginia, Wisconsin
True fir (Western Species)	Alaska, Arizona, California, Colorado, Idaho, Montana, Nevada, New Mexico, Oregon, Utah, Washington, Wyoming
Eastern Hemlock	Alabama, Connecticut, Delaware, Georgia, Indiana, Kentucky, Maine, Maryland, Massachusetts, Michigan, Minnesota, New Hampshire, New Jersey, New York, North Carolina, Ohio, Pennsylvania, Rhode Island, South Carolina, Tennessee, Vermont, Virginia, West Virginia, Wisconsin
Western Hemlock	Alaska, California, Idaho, Montana, Oregon, Washington
Western Larch	Idaho, Montana, Oregon, Washington
Red Pine	Connecticut, Illinois, Maine, Massachusetts, Michigan, Minnesota, New Hampshire, New Jersey, New York, Pennsylvania, Vermont, West Virginia, Wisconsin
Southern Longleaf Pine	Alabama, Florida, Georgia, Louisiana, Mississippi, North Carolina, South Carolina, Texas, Virginia
Sugar Pine	California, Nevada, Oregon
Western White Pine	California, Idaho, Montana, Nevada, Oregon, Washington
Redwood	California, Oregon
Engelmann Spruce	Arizona, California, Colorado, Idaho, Montana, Nevada, New Mexico, Oregon, Utah, Washington, Wyoming

Evaluation

Several different factors can prompt the need for an evaluation of the load-carrying capability of a timber structure, including partial or complete collapse of the structure; structural non-serviceability due to excessive deflection, vibration, or cracking; changes in the use of the structure; changes in the applicable building code, particularly with respect to prescribed loads; fire damage; and reduction in the strength of wood structural members due to damage, modifications, partial failure, deformation, decay, insect attack, or settlement of the structure.

The selection of approaches and methods to be used in structural evaluation is somewhat influenced by the specific reason for carrying out the evaluation. However, there are four distinct phases:

1. inspection of the condition of members and connections, and of the structural environment
2. determination of the loads on the structure
3. structural analysis to determine the effects of loads on individual members and connections
4. assessment of the ability of members and connections to resist the applied loads.

These evaluation steps may be followed by design of reinforcement or by specification of use or occupancy restrictions if the structure proves to be unsafe or unserviceable.

Inspection

Although the inspection of timber structures is described elsewhere in this document, a few points are worth emphasizing here. Regardless of whether the structure is a building (residential, commercial, agricultural, or public), a bridge, a retaining wall, a cooling tower, or any other particular type, there are several specific items that must form a part of the inspection. These items are as follow:

1. The condition of the wood and connections must be ascertained in order to judge whether they are as sound or as good as new materials.
2. The quality of the wood and other elements must be determined in a manner that permits assignment of safe or reasonable allowable stresses. For timber, this usually means that the species must be determined and the individual members must be graded in accordance with one of the current visual stress grading rules.

3. The dimensions of the individual elements and of the structure in general are required in order to permit a structural analysis. Where structural drawings are available, the existing layout and dimensions may be checked against these drawings. Where drawings are not available, the inspection must include a survey of all relevant dimensions.
4. The service environment of the structure must be noted in order that allowable stresses may be properly assigned. Where environments are unusual or severe in terms of temperature, moisture, acidity, or proximity to soil, the conditions should be carefully noted along with the type and degree of protection that has been or can be provided for the wood.
5. Any information related to the magnitude and distribution of loads on the structure should be obtained at the time of inspection. This information must include a listing of the building materials in order to calculate dead loads, and it must also include any features that might affect the magnitude or distribution of superimposed loads.

Determination of Loads

In preparation for the structural analysis phase of an evaluation, it is necessary to have a complete description of the loads that act or might reasonably be expected to act upon a structure during its service life. The load types and their sources are described below:

1. Dead loads include the weights of all permanent materials in or on the structure, including such items as framing members, connections, deck, flooring, roofing, walls, mechanical equipment, and electrical systems. Many structures support permanent fixtures that do not fall into any of the above classifications, and these too, must be taken into account.
2. Loads due to occupancy and use are determined in relation to the intended purpose of the structure. Floor loads may vary greatly depending upon the floor's intended structural use.
3. Snow loads govern the design of many roof structures in areas other than the southern states. Recommended snow loads for various localities are provided by building officials or by the model codes. These recommended loads are based upon observations of snow depth on the ground.
4. Wind loads govern the design of many structural elements, and much of the annual damage to structures is caused by wind.
5. Earthquake loads seldom govern the design of timber structures if all other potential loads have been properly taken into account. Nonetheless, all structures

should be designed to resist moderate earthquakes without significant damage and to resist major earthquakes without collapse.

6. Rain loads occur on roofs where insufficient allowance has been made for drainage.
7. Other loads that may act upon structural elements include those due to thermal or hygroscopic expansion, differential settlement of foundations, and pre- or post-tensioning systems.

Structural Analysis

In the evaluation of a structure, the structural analysis is conducted to identify what types and magnitudes of forces are applied to the individual elements by the loads on the structures, and to determine the stresses and deformations produced in the elements by the applied forces. To perform the structural analysis, it is necessary to model the structure in a way that realistically reflects the response of the entire assembly to the applied loads. The model must include an accurate geometric analog and must be able to deflect in proportion to the stiffnesses of the actual components.

The following design parameters are usually calculated in the analysis of timber structures. The list is not exhaustive but should form a reasonable starting point for any particular structure.

1. *Lumber decking*: deflection and bending stress using appropriate assumptions of continuity based on deck-laying patterns; bearing stress; shear stress (necessary only if the decking is laid on edge rather than flat); stress reversal due to wind uplift; localized high wind suctions at edges of a structure: ability of fasteners to resist uplift forces on decking due to wind suction.
2. *Joists and Purlins*: bending stress; shear stress; bearing stress; deflection; lateral stability. On a sloping or curved roof, oblique joists or purlins should be analyzed for biaxial bending except where there is some other means of resisting the component of load in the plane of the roof, as by diaphragm action, by blocking to the eaves, or by tie rods to the ridge beam.
3. *Diaphragms and Shear Walls*: nail forces due to shear and flexure; axial stress in eave and ridge members, racking loads in "web" materials.
4. *Beams and Girders*: bending stress; shear stress; bearing stress at supports and at points of concentrated applied loads; deflection; additional normal stress due to axial forces applied to beams; lateral stability; stress reversals.
5. *Compression Members*: slenderness in two planes, axial compression stress, bending due to end moments, eccentric compression forces or transverse bending,

possibility of axial stress reversal due to uplift, capacity of lateral supports to provide a minimum of 4 to 5 percent of the axial capacity of the member.

6. *Connections*: check various possible directions of load application. Note that friction should never be considered as a contributor to the capacity of a joint because its contribution cannot be counted on at all times, if drying shrinkage occurs, friction can be greatly diminished. However, in analyzing a collapse, the possible role of friction should be taken into account.
7. *Bracing Members*: axial stresses.
8. *Foundations*: horizontal and vertical reaction forces, including possible uplift forces.

Estimating Load-Carrying Capacity of Structural Elements

The final step in the evaluation of a structural member is to check its ability to resist the applied loads while maintaining a reasonable factor of safety against failure, and to check that deflections are within recommended values. The successful completion of this step for any member assumes that the forces and stresses have been accurately calculated and that allowable stresses and the modulus of elasticity for the member are known. When the loading history on a given structural member is not known with any accuracy and if the member is used under a new loading condition for which it was not originally intended, 90 percent of the normal design stress values otherwise permitted is recommended. It is also important to know the date the structure was designed and built when trying to assess the allowable design stresses and principles used in the design, as both have changed materially over the past 25 years.

It must also be noted that lumber sizes are generally smaller than they were 10 to 15 years ago. For a 2 x 8 in 1981, the approximate change in cross-sectional properties from those of a 2 x 8 prior to 1971 are:

- Cross-sectional area: 11 percent lower
- Section modulus: 14 percent lower
- Moment of inertia: 17 percent lower

Surface appearance of wood can be deceptive. Decay may have begun through the end grain and may not be readily apparent. It may be necessary to take small wood cores with an increment borer for visual examination. It is highly recommended that all test holes in members exposed to adverse conditions be plugged with treated wood plugs or dowels so as not to introduce decay at these locations.

Appendix B: Sample Forms Used for Detailed Wood Inspections

GENERAL INFORMATION ABOUT THE STRUCTURE		
Age of the structure, original structure was built in		
Geographical location of structure?		
Climate, temperature, and moisture conditions?		
Were as-built drawings available?		
Any addition since it was built?		
Any major repair since construction?		
Are memoranda of informal notes available?		
Orientation		
Plan:	Rectangular	
	Irregular	
Type:	Heavy timber building	
	Heavy trusses	
	Light trusses	
	Glued laminated structure	
	Bridges	
	Pole structure	
Number of stories, spans, members, etc.		
Area of structure		
Height of structure		
Was the structure converted to other use since it was built?		
If yes: Use of the building before conversion		
Use of building now		
Occupancy type		
Were there any remodeling to non structural members?		
The quality of material during construction?		
Is wood laminated?		
Is wood visually graded?		
Is wood pressure treated lumber?		
Changes in code requirement, then versus current		
Is there any evidence of settlement		
Remarks:		

LOADS	
Vertical load carrying system	
Lateral load carrying system, masonry wall	
Tributary loading on each structural member	
Low	
Medium	
High but within design	
In excess of design value	
Were point loads considered in original design?	
Were point loads added later to the structure?	
Any point loads applied on weak link in the structure?	
Any local crushing at bearing points such as: Column?	
Girder?	
Bearing wall?	
Any local damage that reduces the type of stress in shear?	
in moment?	
Was the structure overloaded due to: Equipment?	
Addition?	
Ponding?	
Unplanned addition?	
Dynamic vibration?	
Blast?	
Was the structure ever subjected to severe environmental loading?	
Earthquake?	
Hurricane?	
Tornado?	
Fire (check the integrity of bolts)?	
Degradation of long term exposure to high temperature?	
Any sign of wood browning around oven?	
Boiler?	
Processing equipment?	
Are loads used in design available?	
DL?	
LL?	
Lateral?	
Other?	
Estimation of current service load per floor square foot:	
Estimate Factor of Safety:	
Point loads on the structure:	
Conveyors?	
Crane beams?	
Hoists?	
Heaters?	
Air conditioning?	
New layer of roofing?	
Increase in flooring thickness?	
Vibrating equipment compressor?	
Sprinklers?	

PRELIMINARY INSPECTION	
General appearance of structural members?	
Any misalignment?	
Existence of a replaced member?	
Irregularity in roof surface which can collect water?	
Clogged drains or scuppers?	
Size of the drains and scuppers adequacy for rainfall records?	
Any leaks occurred in the past?	
Wall leaks?	
Plumbing leaks?	
Water stains or discoloration of wood?	
Evidence of settlement?	
Evidence of ceiling deflection and distress?	
Any reroofed areas in the roof?	
Sloping in floor?	
Cracks in walls?	
Are exterior walls exposed to rain vulnerable to damage from decay and insects?	
Enclosed spaces with high humidity:	
Attic: Is humidity exhausted into the attic by:	
Inadequate vapor barrier?	
Closed vents?	
Exhausting bathroom?	
Kitchen?	
Clothes-dryer?	
Crawlspace: Is humidity exhausted by:	
Improper installation of soil covers?	
Inadequate or blocked venting?	
Inadequate drainage?	
Food storage and preparation that involve high humidities?	
High temperature (> 80°F)?	
Long exposures to acid or alkaline?	
Chemical storage that absorb moisture from air may lead to corrosion in metal fastenings?	
Air space by wood and barrier to provide ventilation?	

MEMBERS	
Member identification	
Obvious distress in the member	
Distortion, deformation, fracture, or misalignment of structural components in the structure	
Distortion, deformation, fracture, or misalignment of non-structural components in the structure	
Along the member:	
Splits	
Delamination	
Opening	
Grade stamps conform to drawing specification	
If grade stamps are not available, grade may be determined by:	
Knots?	
Cross grain?	
Checks and shakes?	
Is grader able to examine ends of members to determine:	
Rate of growth?	
Percentage of summerwood?	
Is removing cores or plugs necessary?	
Is decay visible?	
is it incipient?	
is it intermediate?	
is it advanced?	
Fungal decay?	
Damage caused by insects?	
Wood degradation due to long term high temperature exposure?	
Evidence of fire exposure?	
Evidence of chemical deterioration?	
Any separations in laminated member?	
(equivalent to seasoning check sawn timbers)	
In the glue?	
In the wood and glue?	
Loads carried by member?	

CONNECTIONS	
Are connection fasteners loose?	
Any connection failure?	
Any sign of wetting around fasteners that enter the structure from surface subjected to wetting?	
Closely fitted surface where drying is slow?	
Deterioration of materials?	
Failure or distress in connection?	
Any splits at connection?	
Any delaminations at connections?	
Any opening at connections?	
Any disengagement of connections?	
Current condition of individual structural members:	
Effectiveness of fastenings and other appurtenance:	
Any decay in portion extent outside the wall and subjected to wetting from rain? roof over flow?	
Were bolts tightened 4-5 months of operating condition?	
Were bolts tightened every 5 year intervals thereafter?	
Beam framed into masonry wall:	
Any decay in portion extending in the wall for lack of ventilation?	
Any trapped water?	
Is laminated member old such that it has bonded with casein adhesive (not water proof)?	
Did damage occur during shipment or erection?	
Did misalignment or miscutting occur during fabricating?	
Did support settle?	
Chord split that may indicate: Loose hardware? Undersize hardware? Omission of shear plates? Split rings during assembly?	
Any teeth bent during installation of toothed truss plates: in a frame? in the trusses?	
Does connection involve stresses perpendicular to grain? Stitch bolts? Other reinforcement to prevent split?	
Are load bearing fittings attached to the supporting member by: Bolts? Lag screws?	
Bolt edge distance of the member?	
Any fastening corrosion?	

BASIC DECAY DETECTION	
Visual:	
Notable change in color?	
Loses luster? (indicates advanced stage of decay)	
Presence of fruiting?	
(does not indicate the degree of decay)	
Dimensional change from moisture?	
Presence of rust?	
Discoloration that indicate leaks from roof?	
Discoloration that indicate leaks from wall?	
Discoloration that indicate leaks from plumbing?	
Touch:	
Softening of surface?	
Abnormal surface shrinkage?	
Sounding:	
Hollow sound (rot)	
Sharp ring (sound wood)	

MATERIAL TESTING FOR DECAY	
Drilling:	
Is it in wet wood? (gives false indication of decay)	
Is it in dry wood	
Reduction of resistance was felt?	
(If yes, indicates the presence of decay)	
Discolored chips and fines?	
(If yes, indicates the presence of decay)	
Coring:	
Boring	
Plug cutter	
Special Devices:	
Shigometer to measure electrical resistance?	
Device involving measuring resistance of a needle?	
Pol-Tec (sonic testing device) to detect internal voids?	
The James "V" meter (transmitter and receiver)?	
Pick Test: (a sliver wood is lifted by a pointed tool)	
A splintering sound (sound wood)	
A brash sound (means decay)	
Moisture Content Meter:	
> 20% (possible decay)	
< 20%	
The wood moisture content at the time of construction?	
Insect Infestation?	

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14. ABSTRACT

This report presents a comprehensive overview of technical information and procedures that are essential for inspecting wood structures and understanding the results. The text addresses wood species characteristics, published structural properties, building code considerations, the effects of environmental factors, and distresses caused by organisms, microorganisms, and nonliving substances such as corrosive chemicals. Inspection procedures covered include guidance on visual identification of wood types, grades, and mechanical stressors; creation of a consolidated wood structure inspection checklist and flow chart; application of qualitative nondestructive field and laboratory tests to determine the basic mechanical properties of the inspected wood materials; and use of qualitative visual inspection procedures that attempt to minimize subjective variations in inspector judgment.

This document is intended to support Army personnel tasked with the field inspection of wood structures but is not intended to serve as guidance or a substitute for structural engineering expertise. If the findings of a wood condition inspection raise concerns or questions about structural integrity, then it is essential to seek the immediate assistance of a trained and qualified structural engineer.

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